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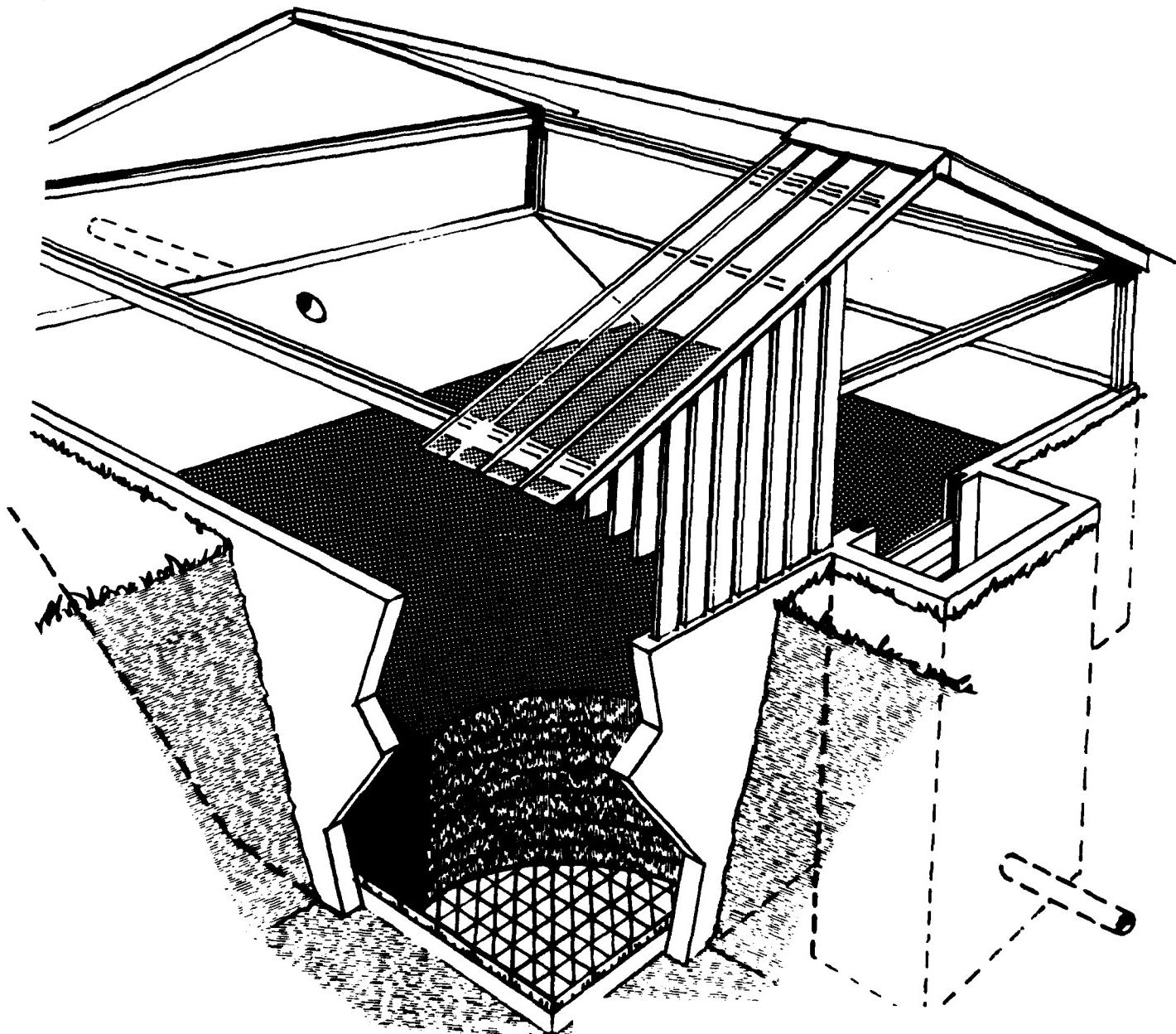
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Development and design of sludge freezing beds



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For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

Cover: Prototype sludge freezing bed.

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Development and design of sludge freezing beds

C. James Martel

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<p>This study develops design criteria for a new sludge dewatering unit operation called a sludge freezing bed. This bed uses natural freeze-thaw to condition the sludge. The total depth of sludge that can be frozen, thawed and dewatered by this process in a year is the main criterion needed for design. Laboratory tests assessed the dewaterability of freeze-thaw conditioned water treatment plant sludge and both anaerobically and aerobically digested wastewater sludges at various depths. Mathematical models for predicting the design depth were developed; values for the input parameters to the models were obtained from the literature or from laboratory and pilot-scale experiments. The dewaterability tests indicated that the depth of sludge that can be applied is not limited by drainability. Up to 2.0 m of each sludge drained in minutes after freeze-thaw conditioning. Except for the aerobically digested sludge, the solids content after drainage is high enough to permit mechanical removal. The physical and thermal characteristics of frozen sludge were found to be equivalent to those of ice. An analysis of the freezing and thawing models reveals that the design of a freezing bed will depend on the duration and intensity of the freezing and thawing seasons.</p>			
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PREFACE

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NOMENCLATURE

A	surface area (m^2)	α	absorptance (dimensionless)
c	specific heat ($\text{W}\cdot\text{hr}/\text{kg}\cdot {}^\circ\text{C}$)	Δ	prefix to indicate change or depth of settled solids (m)
D_f	freezing design depth (m)	ϵ	depth of material (m)
e	rate of change in stored energy (W)	θ	fraction of deposited solids/unit depth of thawed sludge (dimensionless)
E	net change in stored energy	ρ_f	density of frozen material (kg/m^3)
\bar{h}	average convection coefficient ($\text{W}/\text{m}^2\cdot {}^\circ\text{C}$)	ρ_l	density of liquid (kg/m^3)
\bar{I}	average insolation (W/m^2)	τ	transmittance (dimensionless)
K	thermal conductivity ($\text{W}/\text{m}\cdot {}^\circ\text{C}$)		
L	latent heat of fusion ($\text{W}\cdot\text{hr}/\text{kg}$)		
M	net energy transfer with mass flow		
P_f	freezing period (hr)		
q	rate of heat transfer (W)		
Q	net heat energy		
R	net reaction energy		
t	time (hr)		
T	temperature (${}^\circ\text{C}$)		
v	wind velocity (m/s)		
W	net mechanical work		
y	thickness (m)		
Y	depth of frozen sludge (m)		

Subscripts

a	air
c	convection
f	freezing or frozen state
i	ice
k	conduction
r	radiation
s	sludge
th	thawing or thawed state
SS	settled solids

Development and Design of Sludge Freezing Beds

C. JAMES MARTEL

INTRODUCTION

Background

Sludge management continues to be a major problem at both water and wastewater treatment facilities. Although the volume of sludge produced is only a small fraction of the total volume of water or wastewater treated, it consumes over 50% of the operation and maintenance budget. Also, the sludge management problem is expected to increase as the number of higher level treatment processes increases. A recent report by the Water Pollution Control Federation (1982) identifies sludge treatment and disposal as one of the most pressing research needs of this decade.

One of the main problems in sludge management is dewatering. Typically, sludges resulting from wastewater treatment processes contain only 0.25 to 12% solids (Metcalf and Eddy 1979). Water treatment sludges may contain as little as 0.1% solids before thickening and perhaps 2.5% after thickening (Fair et al. 1968). In most cases, direct disposal of these dilute sludges is unacceptable because of the cost of transportation. Also, the liquid in the sludge could pollute surface or groundwaters. Therefore, some method of dewatering is usually required before disposal. Commonly used methods include filter presses, horizontal belt filters, centrifugation, drying beds and lagoons.

For facilities located in cold regions, selection of an effective dewatering method can be especially difficult. Because of the remoteness of many northern communities, parts and equipment are not easily obtainable. Also, most communities are small and skilled operator personnel are scarce or not available. Therefore, complex mechanical dewatering methods are often undesirable. Simpler methods such as drying beds and lagoons can be used but they are inefficient in cold regions because of the shortness of the drying season. In addition, large storage facilities are often required to contain the sludge during the cold and wet winter and spring months.

A more efficient method of dewatering sludges in cold regions is to use natural freeze-thaw. Freeze-thaw is more effective than chemical conditioning for improving sludge dewaterability (Metcalf and Eddy 1979). Some northern plants are already using natural freeze-thaw in their existing lagoons or drying beds. However, these operations were designed to dry sludge and thus are not able to take full advantage of freeze-thaw. To optimize the natural freeze-thaw process, a specially designed unit operation is necessary.

Purpose

The purpose of this study was to develop design criteria for a new unit operation called a sludge freezing bed. The main criterion needed for design is the depth of sludge that can be frozen and thawed naturally at a proposed site. Knowing this value and the volume of sludge generated, one can determine the size or area of the bed.

Scope

The initial objective of this study was to develop a sludge freezing bed concept. This was accomplished by reviewing previous work and visiting three plants with sludge freezing operations.

Several tests were conducted to assess the dewaterability of freeze-thaw conditioned sludges. Dewaterability was measured using specific resistance and capillary suction time tests. The limiting depth for drainage and drying was evaluated in large-scale column studies. Four depths ranging from 30 to 220 cm were tested. Three types of stabilized sludges were used in these tests: a water treatment sludge, an anaerobically digested wastewater sludge and an aerobically digested wastewater sludge. Dewaterability tests were also conducted with these sludges in the unfrozen state.

Mathematical models were developed to predict the design depth based on the natural freezing and thawing energy available at a proposed site. The input parameters to these models were determined from the literature or experimentation. These models were validated using data from other sludge freezing operations.

LITERATURE REVIEW

There is a large body of literature on sludge dewatering by freezing. In addition, there is a significant amount of associated literature on freeze separation of dilute solutions such as seawater. Also, freezing is being considered for isolating and concentrating hazardous wastes. Therefore, the scope of this review was broadened to include these areas.

Two other thorough reviews of this topic have been conducted. One is contained in a Ph.D. thesis by Logston (1971) and the other is in a report for the U.S. Department of the Interior, Office of Water Resources Research (Tilsworth 1972).

Fundamentals of freeze separation

As explained by Glen (1974), ice is a solid that consists of a crystallographic arrangement of water molecules. These water molecules are bonded together by the positive charge concentrations of one molecule in contact with the negatively charged concentration of another. This purely electrostatic attraction between charge concentrations is very strong and plays a major role in determining the mechanical strength of ice.

Because of the highly organized structure of ice, it cannot accommodate other atoms or molecules without severe local strain. As explained by Chalmers (1959), an ice crystal grows by adding water molecules to its structure, as bricks are added to a wall. If a growing crystal comes in contact with other atoms or impurities, it rejects them in favor of water molecules. This process continues until the accumulation of rejected impurities restricts water flow to the crystal.

Rejection of impurities by freezing often occurs in nature. A typical example is the desalination of sea ice. Initially, brine is concentrated between ice crystal boundaries. Over a period of time, this brine drains out by gravity leaving relatively pure ice (Cox and Weeks 1975). Another example is the formation of pure ice from polluted waters. At the turn of the century, all of the ice consumed by the general public was gathered from lakes and ponds during the winter and stored in ice-houses. Sedgwick (1903) noted that very few epidemics could be attributed to infected ice. He concluded that under the quiescent conditions beneath the ice, bacteria and other foreign particles were eliminated by the growing ice front.

Several studies have been conducted to understand the critical factors affecting migration of discrete particles from a planar, solidifying ice front. Corte (1962) demonstrated that an important factor in particle migration is its shape or contact area with the interface. Particles

with large contact areas were easier to displace. Freezing rate was also important. Fine particles migrated under a wide range of freezing rates while coarse ones migrated only at low rates of freezing. All particles were found to migrate at freezing rates less than 1 mm/hr. Uhlmann et al. (1964) found that each particle has a "critical velocity" below which the particle is rejected by the ice front. Continuous rejection of a particle requires both a force preventing incorporation of the particle into the ice and a constant supply of water immediately behind the center of the particle. Cisse and Bolling (1971) found that particles with a greater number of contact points were more easily rejected. They also developed a mathematical model for predicting the interaction of particles with a solidifying front (Bolling and Cisse 1971). The critical trapping velocities of several particles in solutions of naphthalene, camphor, salol and benzophenone were investigated by Kuo and Wilcox (1973). They found that separation was improved by mixing the freezing solution in a horizontal zone refiner, which essentially is a tube rotated about its horizontal axis. Halde (1979) conducted a comprehensive study of the interaction between ice and particles of various sizes. Contrary to Corte (1962), he found that large particles or molecules were more easily separated than smaller ones. Also, vigorous stirring was necessary to maintain particle migration at high freezing rates. Solutions containing higher solids concentrations were more difficult to separate.

When sludge is allowed to freeze naturally, most of the solids are not rejected along a planar front. Instead, the solids become trapped within the frozen sludge (see the *Results* subsection of the *Drainage Tests* section). However, the same mechanism of particle rejection is thought to occur, except that the plane of rejection is along singular or multiple crystal boundaries.

Although solids separation occurs during ice crystal formation, there is a question as to whether the intercrystalline solids are coagulated by compression or dehydration. Studies by Vol'khin and Ponomarev (1965) and Logston (1971) conclude that dehydration is responsible. This conclusion is consistent with the theory of ice lens formation in soils. However, Halde (1979) reasoned that solids are coagulated by the compressive forces of expanding ice. Katz and Mason (1970) concluded that the conditioning effect produced by freezing is a result of both dehydration and pressure exerted on the sludge particles by the ice structure.

Final separation of solids only occurs when the sludge is allowed to thaw and drain. Ezekwo et al. (1980) found that the structural integrity of the remaining solid matrix was an important factor in determining drainability. According to Baskerville (1971) there is a decrease in the drainability of sludges (except for alum sludge) if they are stirred.

Applications of freeze separation technology

Perhaps the most familiar application of freeze separation can be found in the food processing industry. Freeze-drying is used to make instant coffee and to preserve foods. It is also used to preserve biological specimens. In the freeze-drying process, the material is frozen and the ice crystals are removed by sublimation in a vacuum (Mellor 1978). Because of the energy required, this process is not economically feasible for dewatering large volumes of wastewater and water treatment sludges.

Another frequently mentioned use of freeze separation is desalination. This was the first application of freeze separation to receive significant development funding (Heist 1979). Several large pilot plants were built but none are in full-scale operation.

In the area of waste treatment, freeze separation technology has been tried on many types of waste and in many different ways. Generally, however, the reasons for applying this technology are 1) to separate solutes, 2) to dewater sludges, and 3) to concentrate hazardous wastes. Therefore, this review was organized according to these applications.

Separation of solutes

The literature contains several references pertaining to separation of solutes by the freeze crystallization process. This is a direct contact process where a refrigerant is bubbled through a reactor containing the solution to be purified. The refrigerant extracts heat from the solution and causes the formation of a slurry containing ice crystals and concentrate. The ice crystals are then separated in a hydrocyclone or gravity screening device, washed and melted to produce a relatively pure product water. Electroplating wastes, cooling-tower blowdown, pulp-mill bleach streams, and various organic and inorganic effluents from chemical plants have been successfully treated using this process (Iammartino 1975).

Barduhn (1963) and Rose and Sweeney (1963) investigated the feasibility of using the freeze crystallization technique to purify municipal wastewaters. In pilot-scale studies, 90% removal of impurities was achieved by this process. Further tests were recommended to improve the process and reduce costs.

Campbell and Emmerman (1972) evaluated the freeze crystallization process for concentrating plating rinsewater. Greater than 90% removals of nickel, cadmium, chromium, zinc and sodium chloride were achieved in a 9460-L/day pilot plant. The capacity and operating costs were considered to be primarily a function of total flow and, to a limited extent, the initial waste concentration in the feed stream.

Researchers at the Applied Science Laboratories, Inc. (1971) tried five different methods, including freeze crystallization and natural freezing, to purify acid mine water. They selected a freezing technique that involves the formation of an ice layer on the submerged surface of a bayonet-type heat exchanger. When the ice layer was sufficiently thick, the exchanger was removed and the ice discharged. Bench-scale results indicated an 85 to 90% reduction in various metals and acid components using this technique.

A laboratory technique for separating trace organics from aqueous solutions was evaluated by Baker (1967). The advantage of this technique over thermal or solvent extraction is that volatile or reactive compounds are not destroyed. Experimental results indicated that low concentrations of various organics could be effectively concentrated in the absence of dissolved inorganic salts.

Dewatering of sludges

The improved dewaterability of sludges after freeze-thaw has been recognized for several decades. One of the earliest cited reports is that of Babbitt (1931), who noted that activated sludges left on drying beds over the winter drained and dried very quickly after thawing. Since then, there have been several studies to evaluate the potential of sludge freezing as a dewatering process.

Pioneering work on sludge freezing was conducted by Clements et al. (1950). Their more significant findings include:

1. The dewaterability of all sewage sludges was improved by freeze-thaw.
2. Complete freezing was essential but the freezing rate must be fairly slow. "Flash" freezing was ineffective.
3. The method of thawing was unimportant as long as it was not accompanied by vigorous stirring.
4. The quality of the supernatant was similar to that of raw sewage. Also, they developed a freezing machine and conducted tests using digested and activated sludges with and without coagulating chemicals in varying concentrations.

Several references can be found concerning attempts to build a mechanical freezing and thawing device. Doe et al. (1965) proposed a process scheme consisting of 1) gravity thickening with slow picket stirring, 2) storage and decanting for at least 16 hours, and 3) freezing and thawing in a specially designed tank. However, the cost of this process was high because

of the energy requirements and the capital, operation and maintenance costs of the freezing tank (Benn and Doe 1969). Studies by Cheng et al. (1970) indicated that mechanical freezing can be made more economical by a film freezing technique. This technique was tried by the Sewerage Commission of the City of Milwaukee (1971) but the production rates were still not sufficient to compete with other mechanical dewatering processes. In a state-of-the-art review of sludge freezing, Farrell (1971) concluded that mechanical freeze-thaw is greatly limited by the need to freeze slowly.

Instead of freezing the sludge within a tank or on a surface, Randall et al. (1975) and Randall (1978) proposed the use of freeze crystallization. This is the same process that has been tried for separation of solutes (see the *Separation of Solutes* section). Randall concluded that this method results in better conditioning and better supernatant quality than does solid freezing. Also, he concluded that the cost of this process would be competitive with other dewatering processes.

Honda et al. (1981) successfully operated a pilot-scale freeze-thaw device for two years. This device was essentially a shell-tube heat exchanger that was separated into two compartments: a front part for freezing and a rear part for thawing. Sludge was forced into the tubes at the freezing end and thawed at the other end. Reportedly, this device operated automatically and proved to be reliable.

Natural freezing in lagoons or drying beds has been proposed and studied by several investigators (Bishop and Fulton 1968, Medding 1969, Farrell et al. 1970, Bishop 1971, Logston and Edgerly 1971, Mahoney and Duensing 1972, Tilsworth 1972, Rush and Stickney 1979, Reed et al. 1985). These investigators found similar results in that natural freeze-thaw was effective on all types of sludges. Typically, the solids content after drainage was greater than 20%. A snow cover was considered undesirable because it reduced freezing and thawing rates.

The literature contains several reports of actual sludge freezing operations on drying beds and lagoons. Fulton (1970) described plans to build a special sludge freezing basin for the Auburn, New York, Water Treatment Plant. Sludge freezing was successfully demonstrated at several small sewage treatment plants in Finland (Puolanen 1980). Sludge was dewatered from 4.6 to 25-36% solids by freezing on a drying bed with a peat filter bottom. Canfield and Sutphen (1982) reported on a sludge freezing operation at the Lake Ontario Treatment Plant near Oswego, New York. Sludge from the detention lagoon was pumped to several shallow basins at a depth of about 30 cm. The sludge was then allowed to freeze over the winter. Results from the first year of operation indicated that the solids content was increased from 8% to greater than 25%. Sludge from the basins was easily removed with standard earth-moving equipment. Johnson and Doe (1983) concluded that the freeze-thaw method of sludge treatment is working well at the Trap Falls Water Treatment Plant in Sheldon, Connecticut. Frozen in lagoons, the solids content approached 90% in dry weather and had the consistency of coffee grounds. Schleppenbach (1984) reported on a successful sludge freezing operation at the Duluth, Minnesota, water treatment plant. Layers of sludge were frozen by cutting holes in the ice and pumping sludge from the bottom of the lagoon to the surface. Morin et al. (1986) conducted pilot-scale tests with sludge from the Dominion Textile, Inc., plant in Magog, Quebec, Canada, during the winter of 1983-84. Sludge was applied in 2- to 5-cm layers on two pilot-scale lagoons at depths of 1.2 and 0.75 m. They concluded that the maximum allowable solids loading was about 9 kg/m^2 .

Chamberlain and Blouin (1978) conducted studies on the densification of dredged materials by freeze-thaw. They found that freezing and thawing increased the vertical permeability by as much as two orders of magnitude. A natural freezing scheme was proposed in which sequential layers of dredged material would be frozen during the winter months.

Concentration of hazardous wastes

Iskandar (1986) proposed the use of freeze separation to concentrate hazardous wastes in uncontrolled disposal sites. The initial step is to contain the contaminated site by surrounding it with a wall of frozen soil. This wall is created by boring holes around the site to the depth of the underlying confining layer. Pipes are then installed in the holes and connected to artificial refrigeration equipment. The soil between the pipes is rapidly frozen, creating an impermeable wall around the site. Concentration of the hazardous wastes is achieved by progressively freezing inward. The concentrated wastes are removed by pumping. The efficiency of the process is currently under investigation.

Conclusions

Based on this review it was concluded that:

1. The basic mechanism of freeze separation by crystal formation is well understood. However, there is some controversy as to whether sludges are dewatered by compression, dehydration or both.
2. Although freezing by mechanical means such as freeze crystallization has proven to be effective, it is still not cost-competitive with other mechanical or natural dewatering processes.
3. Sludge dewatering by natural freeze-thaw has been successfully demonstrated at a number of water and wastewater treatment plants. However, sludge freezing was not designed into these plants. Instead, each operation is a site-specific modification to an existing lagoon or drying bed. To effectively use this process, a specially designed unit operation is necessary.

CONCEPT DEVELOPMENT

Background

A specially designed unit operation utilizing natural freeze-thaw for sludge dewatering has been proposed by several investigators. Bishop and Fulton (1968) suggested a system with at least two lagoons: one for settling and storing the sludge and another for freezing it in the winter months. The storage lagoon would have a capacity equal to the annual sludge production rate. The freezing lagoon would be sized such that, when decanted before winter, the total remaining depth of sludge would freeze completely.

Farrell et al. (1970) proposed a similar scheme except that the sludge would be frozen in layers by periodically pumping it to a freezing pond. Snow cover would be controlled by plowing, by not pumping when snow is anticipated, or by pumping over the snow to melt it. A method of calculating the depth of frozen sludge was developed based on modified freezing degree-days.

Tilsworth (1972) proposed a system with two lagoons, each designed to handle the entire sludge volume wasted during the year. A sludge depth of 30 cm was selected for application. From April through May, the first lagoon would receive all the sludge up to a depth of 30 cm or less. It would then be allowed to dry in the summer and be removed in the fall. Meanwhile, sludge generated over the summer months would be discharged into the second lagoon to a depth of 15 cm. Once the first lagoon is emptied, it would be refilled with sludge up to a depth of 30 cm over the winter months and allowed to freeze. The remaining capacity in the second lagoon (15 cm) would be used during the spring thaw and drying period.

Rush and Stickney (1979) envisaged a combination drying bed-sludge lagoon consisting of a sand bed with underdrains located in the bottom of a 1- to 3-m-deep lagoon. Several of these lagoons would be necessary. During the summer some lagoons would be used as conventional drying beds. This sludge would remain in the lagoon during the winter until it was

frozen. It would then be removed with large "rototiller" type equipment like that used at Winnipeg, Manitoba (Penman and Van Es 1973). In the winter, sludge would be applied in layers to other lagoons and allowed to freeze. After thawing and drainage this sludge would be removed for final disposal to farmland. Snow cover would be removed or melted with fresh sludge or plant effluent.

Prototype freezing beds were designed and built at three small biological-chemical wastewater treatment plants in Sweden (Hernebring and Lagesson 1986). Each freezing bed was slightly different in design to accommodate site-specific needs. At one installation the bed was divided into two parts: one part was used as a freezing bed and another part was used as a drying bed. Sludge was pumped onto the bed in layers of 5, 10 and 20 cm. The small amounts of snow that fell during the test were removed by applying a layer of sludge to melt the snow. Mechanical removal was planned to handle greater depths of snow.

Site visits

To learn more about the present state of the art, three water treatment plants that claim to use natural freeze-thaw to dewater their sludge were visited. The following is an account of these visits.

Swanton Village, Vermont

Completed in 1979, the Swanton Village Water Treatment Facility was designed to treat 3800 m³/day. Present flow is approximately 1900 m³/day. Treatment processes include chemical coagulation (where alum is added), sedimentation (tube settlers) and filtration (dual media filters). Sludge from the settling compartments and backwash from the filters is pumped to one of two lagoons. Each lagoon is 36 m long by 21 m wide by 1.2 m deep.

According to the facility's O&M manual, sludge freezing can be accomplished by draining out as much supernatant as possible during the fall and allowing the remaining sludge to freeze over the winter. After trying this procedure for two years, the operator found little reduction in sludge depth and the expected granular consistency was never achieved.

A small study was initiated to see if the sludge froze completely when the lagoon was operated according to manual instructions. With the cooperation and assistance of F. Mastriani, Superintendent, one of the lagoons was drained of all supernatant and allowed to freeze over the winter of 1982-83. The initial depth of sludge in the lagoon was 96 cm.

On three separate occasions during the winter (9 December 1982, 25 January 1983 and 7 March 1983), ice cores and sludge samples were taken in each quadrant of the lagoon. An average depth profile of the lagoon observed on each of these dates is shown in Figure 1. This profile indicates that the lagoon never completely froze to the bottom. The maximum ice thickness observed was 29 cm on 7 March 1983. This thickness is probably less than the average because the winter of 1982-83 was warmer than normal. However, it is doubtful that the lagoon would ever freeze completely. Even during the coldest winters, Gow and Govoni (1983) reported that the maximum ice thickness on Post Pond in Lyme, New Hampshire, which has approxi-

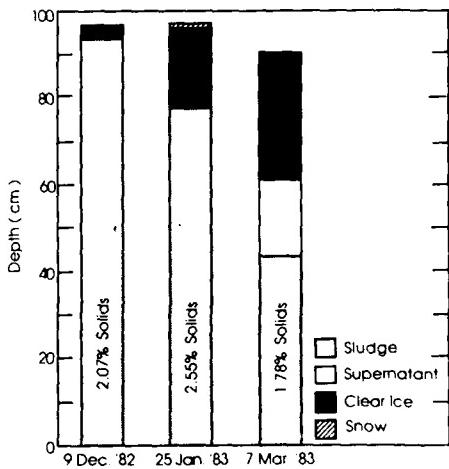


Figure 1. Depth profile of lagoon at Swanton Village, Vermont, water treatment plant during the winter of 1982-83.

mately the same number of freezing degree-days, should range between 40 and 70 cm. Therefore, it is unlikely that the lagoon would ever freeze to the bottom unless the initial depth was lowered considerably.

It is interesting to note that all ice cores were very clear and did not contain sludge particles. This is evidence of the separation process that occurs as the ice front moved downward. This separation caused the solids content beneath the ice to increase from 2.07 to 2.55% between 9 December 1982 and 7 March 1983. The lower solids content observed on 7 March 1983 was probably a result of a previous heavy rainstorm, which washed much of the solids out of the lagoon.

Oswego, New York

The Lake Ontario Filtration Plant, located near Oswego, New York, was visited on 15 March 1983. It has a design capacity of 136,300 m³/day and was designed as a conventional flocculation-settling-filtration plant with upflow clarifiers and dual media filters. However, the plant was converted to a direct filtration system in 1981 to comply with state limitations on discharge of suspended solids into Lake Ontario. These filters are cleaned by "backwashing," which produces large volumes of wastewater with low solids concentration. This backwash water is pumped into two detention lagoons that allow the solid particles to settle out. The supernatant is then discharged into Lake Ontario where it must meet a permit standard of 20.0 mg/L suspended solids.

According to C. Canfield, Plant Manager, sludge freezing has been used since the winter of 1977-78. In the fall, sludge from the bottom of the detention lagoons is pumped to unlined earthen basins called freeze-thawing beds. These beds are filled to a depth of 30 to 45 cm and allowed to freeze over the winter. At this depth the sludge freezes completely, even under a snow cover. In the spring, the beds are allowed to thaw naturally and the remaining water evaporates or percolates into the ground. By July or August the sludge has dried to 25 to 30% solids and has characteristics ranging from powdery and clay-like to granular and sand-like. Finally, the sludge is removed with standard earth-moving equipment and trucked to a nearby containment area.

Duluth, Minnesota

The Lakewood Water Treatment Plant in Duluth, Minnesota, which draws water from Lake Superior, has an average design flow of 113,500 m³/day. The treatment processes include screening, chemical coagulation with alum and polymers, and multi-media filtration. Backwash from the filters is pumped to a clarifier, which concentrates the sludge and sends the clarified supernatant back through the treatment processes. The clarifier underflow is pumped to three lagoons where further sedimentation occurs and the supernatant is returned to the plant.

During a visit to the plant on 17 March 1983, F. Schleppenbach, Manager of the Water and Gas Division, stated that the sludge-freezing operation has been working for five years. Because of the effectiveness of this operation in reducing sludge volume, the lagoons have not needed emptying during this period. This is fortunate because the sludge contains asbestos fibers that could make ultimate disposal difficult.

Duluth uses the freezing process by draining all supernatant from two of three lagoons and allowing them to freeze over. When the ice is thick enough to support men and equipment (about 10 cm), holes are bored into the ice and the sludge is pumped onto the ice where it freezes. After the sludge layer is completely frozen, another layer is pumped to the surface. This operation continues all winter until the lagoon is empty or the freezing season is over. Sludge generated during winter is frozen by spraying it into the third lagoon. Spraying was found to be necessary to evenly distribute the sludge. Snow is removed with a snowblower.

Final concept

Based on ideas obtained from the literature and the site visits, it was concluded that the essential design features of a freezing bed were as follows:

1. It should be designed so that sludge is applied in several thin layers rather than a single, thick layer. Each layer should be applied as soon as the previous layer has frozen. This will increase the freezing rate and maximize the total depth of sludge that can be processed.

2. The bed should be covered to prevent snow from accumulating on the surface. This feature is critical if the unit is to operate as designed. An open freezing bed would be difficult to design because of the unpredictability of snow removal operations. Also, snow removal would be practically impossible if there was a large snowfall soon after sludge was applied. In this case the operator would have to delay snow removal until the frozen sludge was thick enough to support snow removal equipment. This could take several days, depending on the depth of snow.

3. The sides of the bed should be left open to allow free air circulation. However, a half-wall or louvered wall may be necessary to control drifting snow.

With these thoughts in mind, a conceptual sketch of a sludge freezing bed was developed (Fig. 2). Essentially, it is a large in-ground concrete tank with a ramp on one side and an overflow gate on the other. A ramp is needed to allow vehicle access for sludge removal and to distribute the incoming sludge evenly within the bed. An overflow gate is provided in case of accidental overfilling, and to draw off supernatant during thaw. The bottom of the bed is under-drained with wedgewire screen or sand to allow drainage of the filtrate. Both overflow and filtrate are collected in a sump and pumped back to the plant.

To use the bed the operator would apply sludge in layers during the winter months. At the end of the freezing season, applications would be stopped and the frozen sludge layers would be allowed to thaw. Under natural ambient conditions, thawing is expected to proceed from the top downward. Most of the supernatant could be drained away by removing stop-planks from the overflow gate. When thawing is complete, any remaining liquid could be drained away through the wedgewire or sand bottom. If necessary, the sludge could be kept in the bed until the desired solids content is achieved. The operator would then remove the sludge

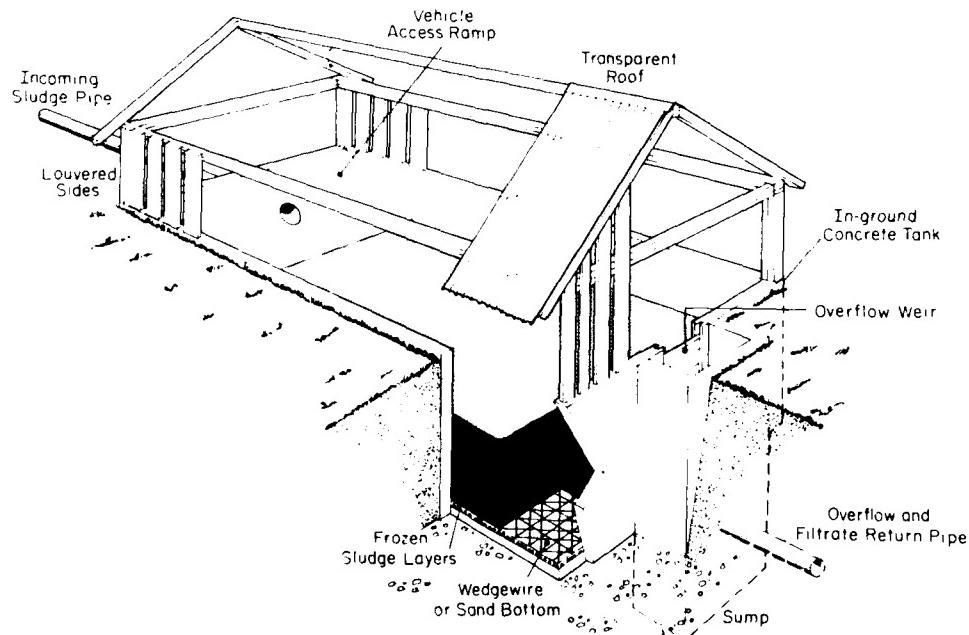
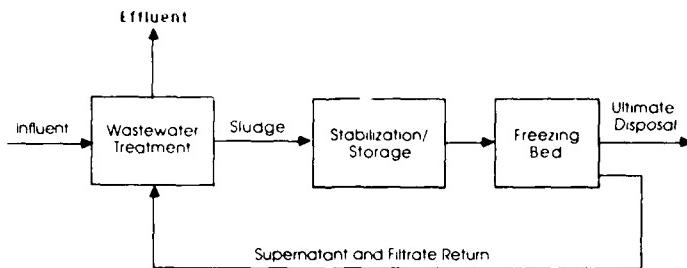
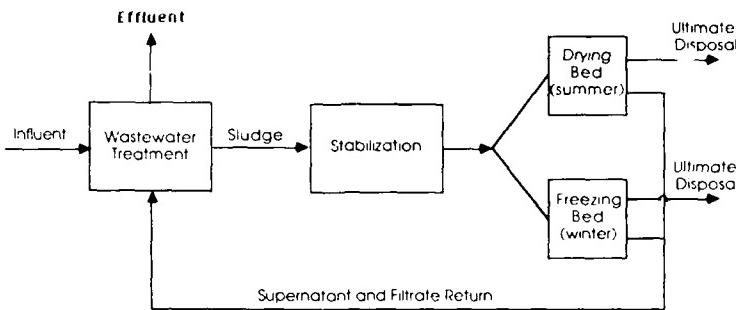


Figure 2. Conceptual sketch of sludge freezing bed.



a. Freezing bed as sole method of dewatering.



b. Freezing bed in combination with drying bed.

Figure 3. Process flowsheets for sludge dewatering with freezing beds.

with a front-end loader or other device. If sufficient warm weather remains, the operator could continue sludge dewatering by using the freezing bed as a drying bed.

As conceived, a sludge freezing bed could be used as a sole method of dewatering (Fig. 3a) or in combination with other methods such as drying beds (Fig. 3b). If used as the only method of dewatering, a storage facility will be necessary to contain the sludge during the summer months. This storage facility could be a lagoon, tank or even a digester if excess capacity was available. When used in combination with other methods, it would be designed to handle the winter sludge production only. A freezing and drying bed combination is particularly attractive because both dewatering operations are conducted under naturally optimum conditions.

To maximize the depth of sludge in the bed, each layer should be applied as soon as the previous layer has frozen. This could be difficult to accomplish unless the plant is manned 24 hours per day, 7 days per week. Instead, it may be possible to automate the bed using a thermostatic controller. The controller could begin pumping of a new layer once a preset number of degree-hours or -days had elapsed. A model for predicting the time needed to freeze a layer of specified thickness can be found in the *Development of Design Models* section.

The relative cost of dewatering sludge by this method is expected to be significantly less than mechanical systems because minimal energy is needed. Also, there is no need for chemical conditioning. Compared to drying beds, the construction costs should be similar because they are similarly constructed. However, the O&M costs of a freezing bed should be less because sludge would normally be removed only once per year and with the aid of mechanical equipment.

DEWATERABILITY STUDIES

The size of a freezing bed will depend on the volume of sludge generated by the plant and the depth of sludge that can be applied. The sludge volume can be estimated based on wastewater characteristics and flow, but the depth of sludge is unknown. Past experience is confined to drying beds, which normally receive only 30 to 40 cm of sludge per application. Potentially, the freezing bed could receive several times this depth over the winter. The question then arises as to whether this sludge will drain and dry adequately even after freeze-thaw. To answer this question, a series of dewaterability studies were conducted. Three common sludges were selected for evaluation: a water treatment sludge, an anaerobically digested wastewater sludge and an aerobically digested wastewater sludge.

Sludge characteristics

The water treatment sludge was obtained from the Lebanon, New Hampshire, Water Treatment Plant. This plant has a design flow of 15,140 m³/day. Treatment processes include rapid mixing with potassium permanganate and alum addition, pH control with soda ash, flocculation, sedimentation, rapid sand filtration and chlorination. Sludge is dewatered by evaporation and filtration in a shallow, gravel-bottomed basin.

The anaerobically digested sludge was collected at the Hanover, New Hampshire, Waste-water Treatment Plant, which has a design flow of 5700 m³/day. Primary treatment only is provided and the sludge is stabilized in an anaerobic digester. Sludge from the digester is periodically withdrawn and dewatered on drying beds.

Aerobically digested sludge was obtained from the Woodstock, Vermont, Wastewater Treatment Plant. Present flow at the plant is approximately 1700 m³/day and treatment is achieved using the contact stabilization process. Waste-activated sludge is aerobically digested for approximately 10 days and then spread on land in the summer.

The initial physical characteristics of each sludge are shown in Table 1. These characteristics are typical of each type. All analyses were performed in accordance with Standard Methods, 15th Ed. (APHA 1980).

Specific resistance and capillary suction time

Specific resistance and capillary suction time tests were conducted on all three sludges, before and after freeze-thaw conditioning. The freeze-thaw conditioned sludge samples were frozen at -10°C for seven days.

Specific resistance tests were conducted using the procedure developed by Adrian et al. (1968). The best results were obtained using a Whatman No. 5 paper for the water treatment and aerobically digested sludges, and Whatman No. 1 paper for the anaerobic sludge. After freezing, the solids had a tendency to separate from the liquids and settled to the bottom of the Buchner funnel. This made it difficult to take a representative sludge sample. To avoid this problem the solids content (after drainage) was determined by dividing the total mass of cake solids by the volume of filtrate generated at the end of the test, as suggested by Christensen and Dick (1985).

The results of the specific resistance tests before and after freeze-thaw are shown in Table 2. The specific resistance of water treatment sludge decreased slightly after freeze-thaw,

Table 1. Initial physical characteristics of sludges.

Sludge type	Total solids (%)	Volatile solids (%)	Specific gravity
Water treatment	0.9	52	1.005
Anaerobic	8.7	48	1.006
Aerobic	1.5	77	1.005

Table 2. Dewaterability of sludge before and after freeze-thaw.

Sludge type	Specific resistance (s ¹ /g @38.1 cm Hg)		Coefficient of compressibility (dimensionless)		Capillary suction time (s)	
	Before	After	Before	After	Before	After
Water treatment	4.8×10^9	6.0×10^9	1.53	2.79	32	6
Anaerobic	1.5×10^9	1.7×10^9	0.69	0.74	212	57
Aerobic	2.1×10^9	1.3×10^{10}	0.14	1.18	37	11

whereas it increased for both wastewater sludges. An increase in specific resistance indicates a degradation in dewaterability, which is contrary to observed results. However, this anomaly is not unusual with freeze-thaw conditioned sludges. Rush and Stickney (1979) obtained similar results. In Adrian and Nebiker (1969), Roule concluded that specific resistance may not be a valid dewaterability parameter for freeze-thaw conditioned sludges because of the rapid separation of solids from liquids. Apparently, these solids clog the filter paper when a vacuum is applied causing a high specific resistance measurement.

As shown in Table 2, the coefficients of compressibility for all three sludges increased as a result of freeze-thaw. This implies that the sludge will be easily compressed, and dewatering will be more difficult. Again, these results contradict the fact that freeze-thaw improves dewaterability. However, each coefficient was determined from a specific resistance test, which, as mentioned earlier, is an inappropriate test for freeze-thaw conditioned sludges. Therefore, the coefficients of compressibility, which were determined from this test, are meaningless.

Capillary suction time (CST) is a more recently developed measure of sludge dewaterability (Baskerville and Gale 1968). It is the time taken by a constant volume of filtrate, acting under the influence of capillary suction pressure, to saturate a piece of filter paper. The rate at which the paper becomes wetted is an indication of the filterability of the sludge. The lower the CST, the better the filterability of the sludge.

CST values for each sludge were measured using the Komline-Sanderson Capillary Suction Timer (Fig. 4). Five tests were conducted on each sludge to determine an average value. Based on a statistical analysis of previous CST data, this value should be within $\pm 10\%$ of the true mean at the 95% confidence limit.

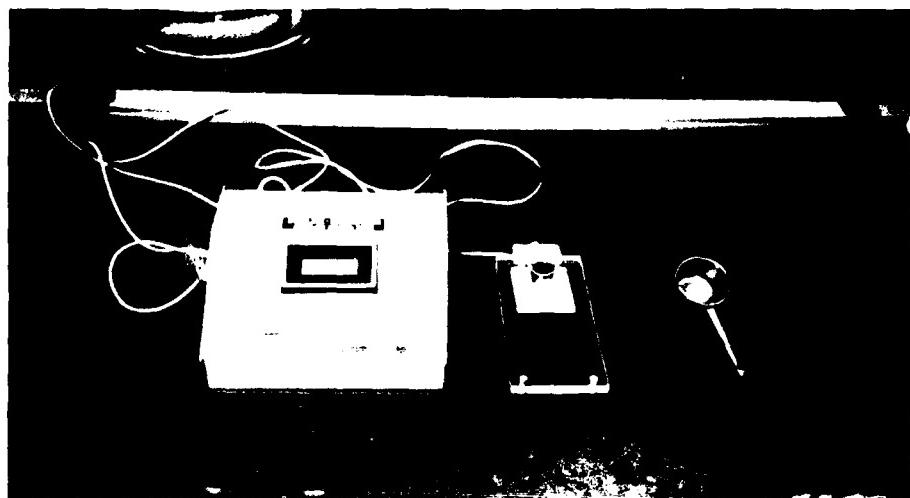


Figure 4. Komline-Sanderson Capillary Suction Time (CST) device.

Unlike the specific resistance tests, the CST tests showed a definite improvement in sludge dewaterability after freeze-thaw. For example, the water treatment sludge had a CST of 32 seconds before freezing and only 7 seconds after freezing (see Table 2). Similar results were obtained with the anaerobically and aerobically digested sludges. Rush and Stickney (1979) noted similar reductions in their study. Thus, for freeze-thaw conditioned sludges, the CST test appears to be a better indicator of relative dewaterability.

Filtrate quality

To determine the effect of freezing on filtrate quality, the filtrate obtained during the specific resistance tests was analyzed for 5-day Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), turbidity and pH. All analyses were conducted according to Standard Methods, 15th Ed. (APHA 1980).

Examination of these data (see Table 3) indicates that freeze-thaw reduces the quality of the filtrate. Turbidity, BOD and COD concentrations were all higher in the filtrate from the freeze-thaw conditioned sludges. The reason for this decrease is not known but it may be the release of interstitial waters that contain higher concentrations of dissolved materials than the surrounding free water. Similar results were obtained by Rush and Stickney (1979), who concluded that BOD, COD, Total Organic Carbon (TOC) and total phosphorus concentrations in the filtrate were three to six times higher than those in raw sewage. However, their mass balance calculations indicated that even during the most rapid spring thawing conditions, the hydraulic and organic loads to a plant would increase by less than 0.8 and 5.0%, respectively.

Table 3. Filtrate quality before and after freezing.

Sludge type	BOD (mg/L)		COD (mg/L)		Turbidity (NTU)		pH	
	Before	After	Before	After	Before	After	Before	After
Water treatment	—	—	—	—	1.4	2.7	5.3	5.2
Anaerobic	117	459	500	1064	58	72	8.2	7.8
Aerobic	51	65	117	230	3.4	43	7.4	7.5

Drainage tests

The limiting depth for each sludge was evaluated by conducting a series of drainage tests at four depths ranging from 30 to 220 cm. Both freeze-thaw conditioned and unfrozen sludges were used. The reason for testing unfrozen sludges was to provide a basis for comparison. All tests were conducted during the spring and summer of 1985 in CRREL's greenhouse.

Materials and methods

The drainage tests were conducted in 15-cm-diameter clear cast acrylic columns. Each column was attached to a funnel-shaped base, which was machined from a solid piece of acrylic. The filter media at the base of each column consisted of 15 cm of 20-30 Ottawa sand underlain by 1- to 3-cm-diameter support gravel. A sheet of black polypropylene geotextile was used to separate the sand and the gravel. Another sheet of the same material was placed over the sand surface to provide a clean base for core sampling of sludge. To maintain an equal reference head, each column was connected to a constant head tank. A sketch of these components is shown in Figure 5.

Eight columns, one pair for each depth, were constructed. Each column was graduated in centimeter increments from the bottom to the top. For easier observation of sludge depth, the columns were mounted on a white backboard. The columns were numbered sequentially

1 through 8 from tallest to shortest. The odd-numbered column of each pair received unfrozen sludge while the even-numbered column received an equal amount of frozen sludge. Photos of these columns are shown in Figure 6.

Sludge could not be frozen inside the columns because expansion forces would cause them to fracture. To circumvent this problem sludge was frozen in the form of individual cakes. Each cake contained 1400 to 1700 mL of sludge and was sized to fit snugly inside the column. These cakes were then stacked in the even-numbered columns. This technique closely simulated the layered configuration of a sludge freezing bed.

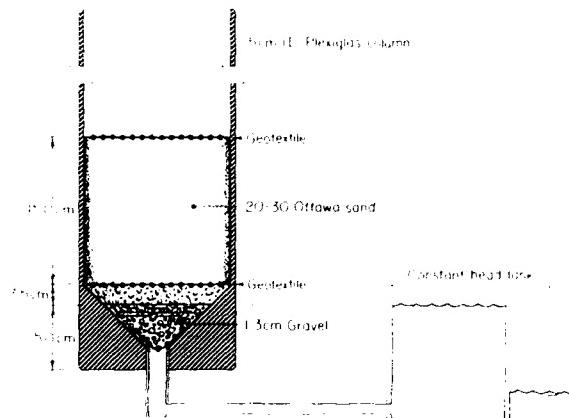


Figure 5. Column used in drainage and drying tests.



a. Columns 1, 2, 3, 4.



b. Columns 5, 6, 7, 8.

Figure 6. Columns used in drainage tests.

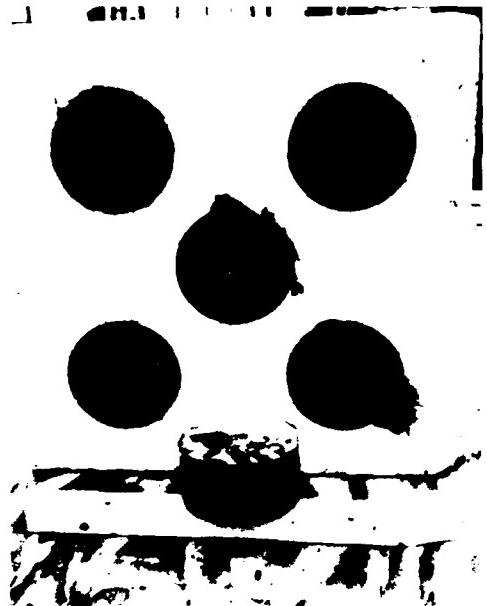


Figure 7. Polystyrene tray used to freeze sludge cakes. Five cakes were frozen in each tray. A sludge cake is visible in the foreground.

The sludge cakes were made by freezing sludge in several trays made of expanded polystyrene insulation. The insulation reduced the freezing rate from the side and bottom, which more closely simulates natural freezing from the top only. Five 15-cm-diameter by 15-cm-deep holes were drilled into each tray using a specially fabricated bit. The sides of the hole were tapered outward to promote easier extraction of the frozen sludge cakes. The inside surfaces of the holes were waterproofed with a flexible rubberized membrane, and a thin coating of petroleum jelly was spread over the membrane to facilitate cake removal. A "sludge cake" and freezing tray are shown in Figure 7.

Drainage tests were initiated on the unfrozen sludge soon after it was collected and transported to CRREL. Upon arrival, the sludge was placed in a large container



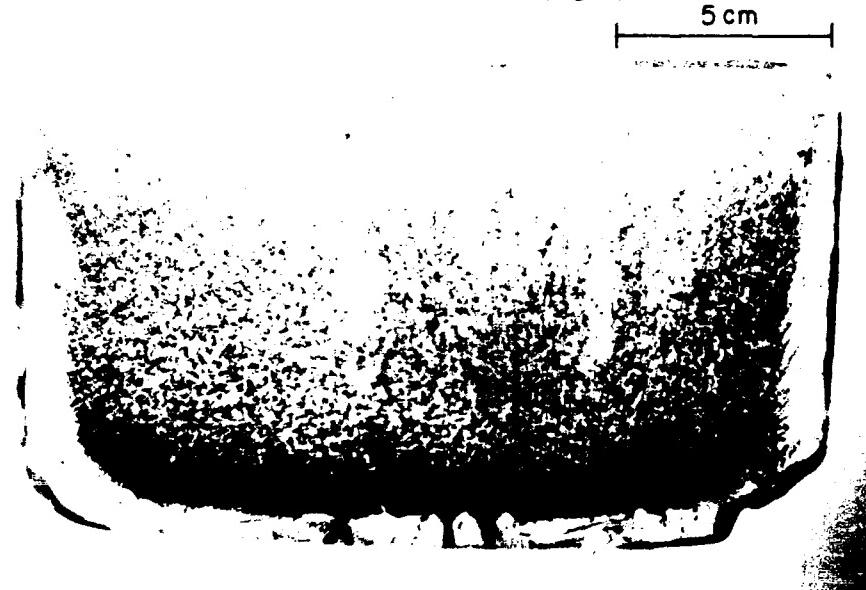
Figure 8. Pouring unfrozen sludge into column 3.



Figure 9. Stacking sludge cakes in column 6.

and continuously mixed to maintain homogeneity. This sludge was placed in each odd-numbered column by direct pouring, as shown in Figure 8. To prevent scouring, a circular splash plate was placed over the fabric-covered Ottawa sand. When all four odd-numbered columns were filled, the valves were opened simultaneously and the sludge was allowed to drain.

While the unfrozen sludge was draining, the remaining sludge was poured into the freezing trays. The trays were transported to a coldroom and frozen for about seven days. When completely frozen, the sludge cakes were ejected by dropping the tray in an upside-down position onto a hard surface. The cakes were then stacked (Fig. 9) in the even-numbered col-



a. Lebanon, New Hampshire, water treatment sludge, 1.1% solids.



b. Fort Drum, New York, anaerobically digested sludge, 3.7% solids.

Figure 10. Thin sections of frozen sludge cakes.

umns to a depth equivalent (after allowing for expansion) to the sludge depth in the adjacent odd-numbered columns. The cakes were allowed to melt overnight before the drain valves were opened.

As each column drained, sludge depths were recorded with time. Drainage was assumed to be complete when the Ottawa sand no longer looked saturated.

Results

Prior to conducting the drainage test, vertical thin sections were cut from selected sludge cakes to observe the effect of freezing. Approximately 0.3 cm thick, each thin section was mounted on a glass plate and placed on a light table in a coldroom. Photos of two thin sections are shown in Figure 10.

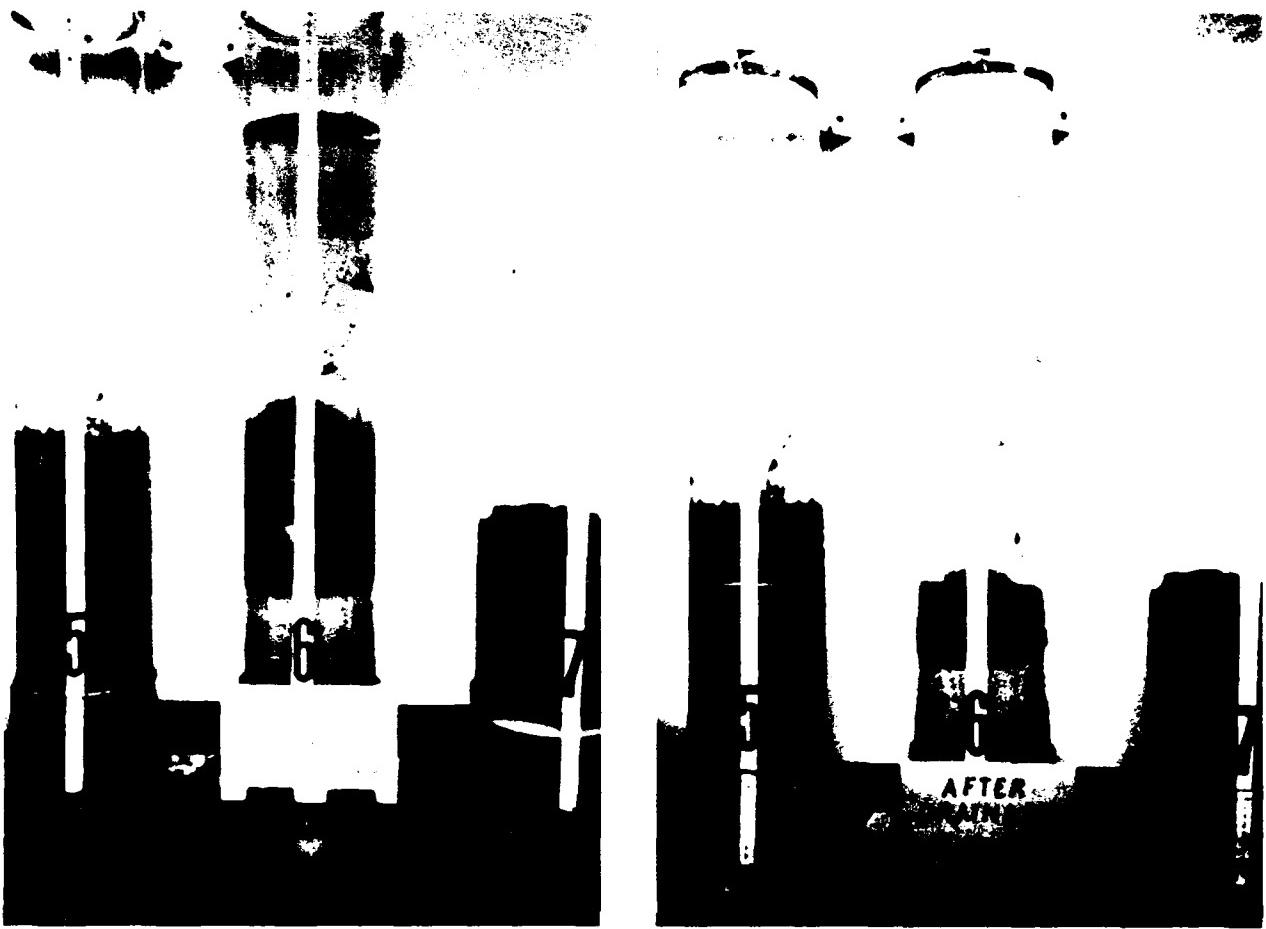
Inspection of these photos reveals several transparent zones of relatively clear ice. The zones of clear ice along the sides and bottom are an indication that the freezing rate was slow enough for solids to be rejected ahead of the advancing ice front. The freezing rate was slower in these areas because of the insulation. At the top surface the sludge was in direct contact with the cold ambient air. In the case of the dilute Lebanon sludge (Fig. 10a), the freezing rate was still slow enough to exclude most solids up to a depth of approximately 3 cm. As the ice front advanced, more and more particles became trapped between ice crystal boundaries. The rejection of solids to ice crystal boundaries is clearly evident in the thin section of a Ft. Drum sludge (Fig. 10b). Whether the solids were rejected along a front or between ice crystal boundaries the effect was the same, i.e., a separation of solid and liquid fractions.

As the cakes in the columns thawed, large angular fragments were observed falling to the bottom where they accumulated to form a loose aggregate. Overlying the solids aggregate was the relatively clear supernatant. When the drain valve was opened, the overlying supernatant rapidly permeated this aggregate although some consolidation was observed. In contrast, the solid particles in the unfrozen sludge remained finely divided, forming an increasingly dense blanket that became relatively impermeable. These observations were common to all three sludges tested. Photos of a column containing freeze-thaw conditioned aerobically digested sludge before and after drainage are shown in Figure 11.

Data from the drainage tests on the water treatment sludge are plotted in Figure 12. The unfrozen sludge drained very slowly, especially in columns 1 and 3, which were still draining after 21,000 minutes (14.6 days). In sharp contrast, drainage of the freeze-thaw conditioned sludge proceeded very quickly. For example, column 2, which contained 220 cm of freeze-thaw conditioned sludge, drained in only 6.5 minutes.

Drainage curves for the anaerobically digested sludge are shown in Figure 13. Again the columns containing the unfrozen sludge drained very slowly. Surprisingly, the sludge level in these columns increased during the early part of the drainage period. This rise was caused by floating sludge produced as a result of gas formation. This did not occur with the freeze-thaw conditioned sludge, which drained very rapidly. For example, it took only 111 minutes to drain 2.0 m of freeze-thaw conditioned sludge vs 29,000 minutes (20 days) for the same amount of unfrozen sludge.

As shown in Figure 14, similar results were observed during drainage tests on the aerobically digested sludge. Columns containing the unfrozen sludge drained slowly and experienced the same rising sludge problem noted during the previous tests with anaerobically digested sludge. After 21,000 minutes (14.6 days), 2.0 m of unfrozen sludge was still draining, while the same depth of freeze-thaw conditioned sludge drained in only 18.5 minutes.



a. Before drainage.

b. After drainage.

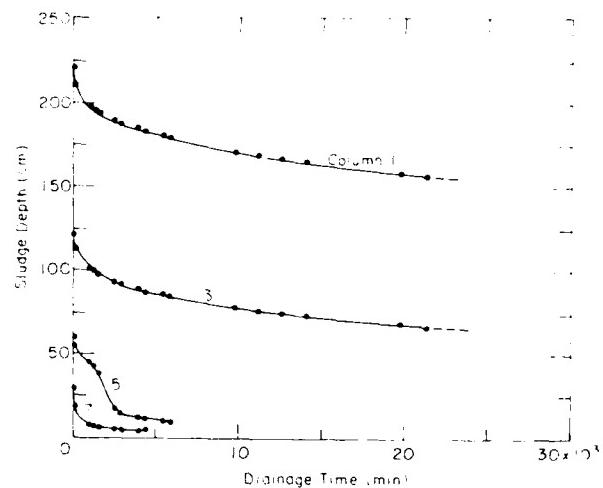
Figure 11. Freeze-thaw conditioned aerobically digested sludge before and after drainage.

Discussion

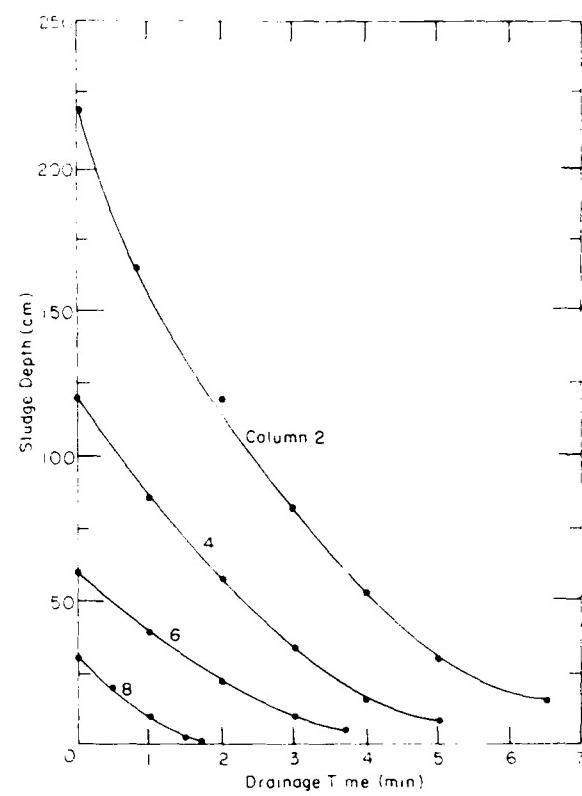
The drainage tests clearly demonstrated the remarkable improvement in drainability attributable to freeze-thaw. All columns containing the freeze-thaw conditioned sludges drained in minutes compared to days for the equivalent depth of unfrozen sludge. This happened for all three sludges tested. Thus, it is reasonable to expect that up to 2.0 m of these sludges could be applied to a freezing bed. Considering the rapid drainage of all sludges at this depth, even greater depths may be possible.

An attempt was made to use a model developed by Nebiker et al. (1968), Sanders (1968) and Clark (1970) to predict drainage times. This attempt was not successful because the model predicted much longer drainage times than were actually experienced. For example, the model predicted a drainage time of five days for 2.0 m of anaerobically digested sludge where the actual drainage time was only 111 minutes. Presumably, this lack of agreement was ascribable to a physical change in sludge particle size caused by freeze-thaw. Instead of a suspension of finely divided particles, which the model assumes, the sludge was converted to a slurry of settleable particles in water.

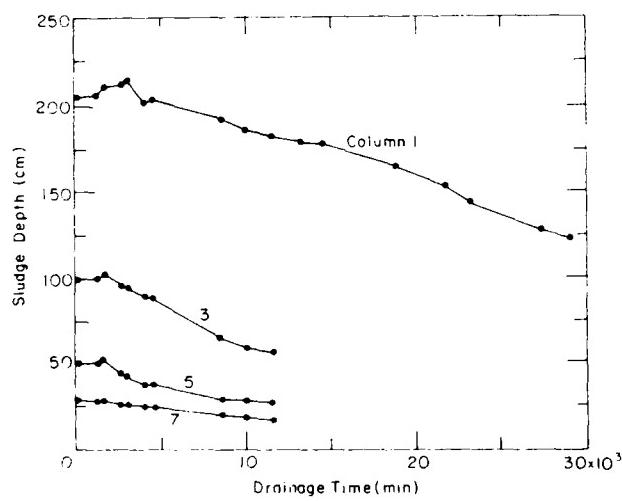
Because of the short drainage times experienced with freeze-thaw conditioned sludges there is no practical need to develop a drainage model for design. Also, most of the water could be removed from the freezing bed as supernatant rather than filtrate. In addition, if



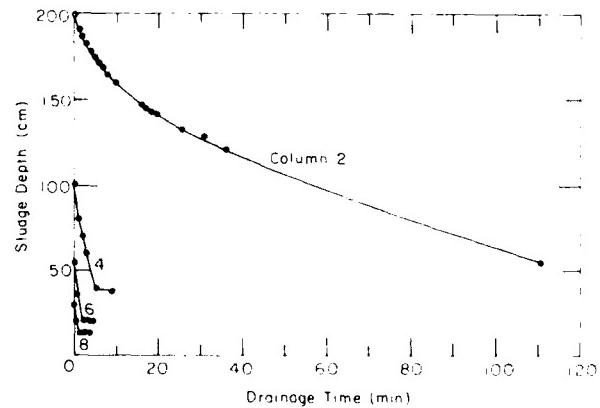
a. Unfrozen.



b. Freeze-thaw conditioned.



a. Unfrozen.



b. Freeze-thaw conditioned.

Figure 12. Drainage curves for columns containing water treatment sludge.

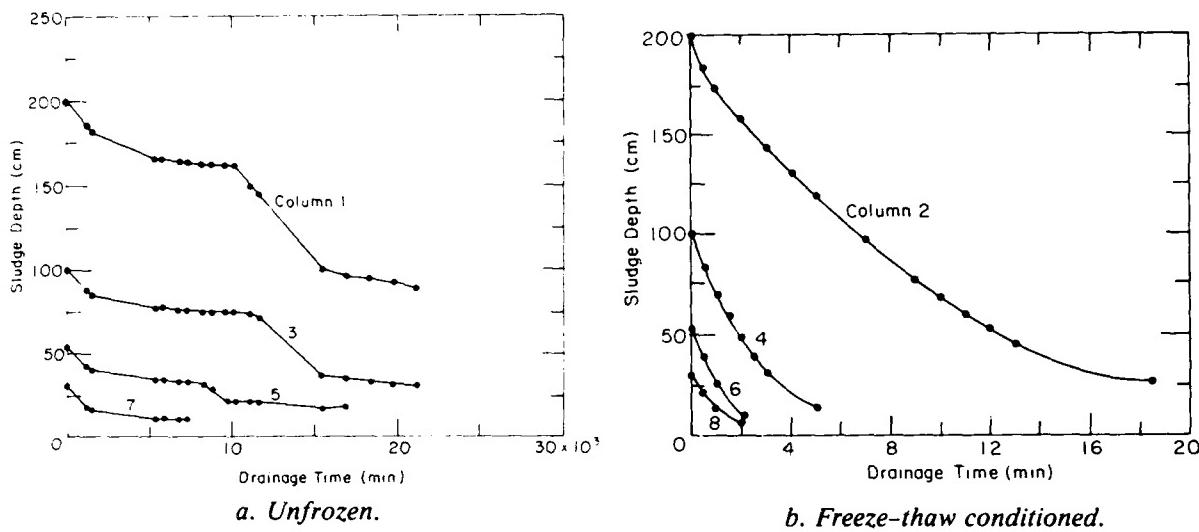


Figure 14. Drainage curves for columns containing aerobically digested sludge.

filtration was allowed to take place simultaneously with thawing, then the slower thawing rate would control the rate of drainage.

Drying tests

The end of the drainage period marked the beginning of the drying rate studies. Drying tests were conducted by leaving the sludge in the drainage columns for several days. Periodically, core samples were taken and analyzed for total solids.

Materials and methods

Sludge samples were taken with a coring device made from a 2.54-cm-diameter brass pipe. The pipe was slowly pushed into the sludge layer until it contacted the geotextile sheet. The sample was then extracted with a plunger. This technique provided a composite sample of the vertical cross section. All sludge samples were analyzed for total solids content according to Standard Methods, 15th Ed. (APHA 1980).

Results

As shown in Table 4, the total solids content of the freeze-thaw conditioned water treatment sludge after drainage ranged from 28.2 to 31.6% and averaged 30.3%. An increase in solids from 0.9 to 30.3% means that 97% of the water was removed from the original sludge. In contrast, the average solids content in the drained unfrozen sludge was only 9.8%.

Table 4. Total solids content after drainage of freeze-thaw conditioned sludges.

Column	Water treatment	Total solids content (%)	
		Anaerobic	Aerobic
1	—	17.2	5.9
2	30.1	37.0	16.6
3	—	21.2	6.8
4	28.2	36.3	17.5
5	10.4	23.0	6.0
6	31.6	33.0	16.7
7	9.3	19.1	7.3
8	31.2	34.2	15.6

The average solids content in the freeze-thaw conditioned anaerobic sludge after drainage was 35.1%. This increase represents a 75% removal of water. The unfrozen sludge contained an average of 20.1% solids.

From Table 4 the average solids content in the freeze-thaw conditioned aerobically digested sludge was 16.6%, which means than 91% of the water in the original sludge was re-

Table 5. Drying rate data for freeze-thaw conditioned sludges.

Drying time (hr)	Total solids content (%)			
	Column 2	Column 4	Column 6	Column 8
a. Water treatment sludge				
0	30.1	28.2	31.6	31.2
21	31.7	—	—	—
49	—	28.9	60.9	44.9
97	32.3	—	—	—
125	—	34.3	43.8	72.7
188	34.6	—	—	—
217	—	34.1	36.3	38.5
308	37.5	—	—	—
337	—	41.1	—	—
430	39.5	—	—	—
b. Anaerobically digested sludge				
0	37.0	36.3	33.0	34.2
96	40.8	—	—	—
120	—	43.3	42.7	44.7
168	42.8	—	—	—
192	—	46.0	43.4	55.7
c. Aerobically digested sludge				
0	16.6	17.5	16.7	15.6
66	17.0	18.0	18.4	19.3
165	23.6	20.1	23.6	23.4
236	19.3	18.5	26.6	21.6
335	19.7	21.4	34.6	38.1
405	20.7	21.6	36.2	45.9
550	16.9	21.1	—	—
715	19.2	24.2	—	—

moved. The average solids content in the odd-numbered columns containing the unfrozen sludge was only 6.5%.

Drying rate data for each of the drained sludges are shown in Table 5. Generally, the solids dried more quickly in the columns containing less sludge. For example, after drying for 405 hours (almost 17 days) the solids content in column 8 (Table 5c) was 45.9%. During this same period, the solids content in column 2 was only 20.7%. Originally, the depth of sludge in columns 2 and 8 was 30 cm and 200 cm, respectively.

Contrary to expectations, the solids content in some of the columns seemed to decrease with increasing drying time. For example, the solids content in column 6 after 49 hours of drying time (Table 5a) was 60.9%; 76 hours later the solids content was lower at 43.8%. What caused this reduction? A check of the analytical data did not reveal any errors. The only reasonable explanation seems to be that some portions of sludge in the columns dried faster than others. Thus the core sampling technique may not have always provided a representative sample of the entire contents of the column.

Discussion

After drainage, the solid contents in the water treatment and anaerobically digested sludge were greater than 20%. According to WPCF (1983), this solids content is high enough to permit mechanical removal by a front-end loader or truck-mounted vacuum. Therefore, further dewatering by drying does not appear to be necessary with these sludges.

Based on the WPCF criteria, only the freeze-thaw conditioned aerobically digested sludge would require further dewatering by drying. This may take several days depending on the depth of sludge in the bed. According to the drying rate data shown in Table 5c, the times needed to achieve 20% solids in columns 8, 6, 4 and 2 were approximately 66, 165, 335 and 405 hours respectively.

The reason for a lower solids content in the aerobically digested sludge than in the other sludges was not clear. Perhaps the reason is related to the greater volatile solids content of aerobically digested sludges (see Table 1). Rush and Stickney (1979) noted similar results in experiments conducted with both digested and undigested sludges. The digested sludges, which contained less volatile solids, were dewatered more efficiently than the undigested sludges.

No attempt was made to use the model developed by Nebiker (1967) to predict the total drying time for the freeze-thaw conditioned sludges. The initial moisture content of these sludges (after drainage) was already lower than the critical moisture content. This means that dewatering had already progressed beyond the constant-rate drying period, which violates an assumption of his model.

The greatest mass of sludge in terms of dry solids content was applied to columns 1 and 2 during the tests on anaerobically digested sludge. At 8.7% total solids and a depth of 2.0 m, the total mass of dry solids was 3.09 kg, or 174 kg/m² on a per unit area basis. If applied annually this mass is equivalent to a bed loading of 174 kg/m²·yr. By comparison, typical loadings for open drying beds range from 50 to 125 kg/m²·yr (WPCF 1983). Therefore, a sludge freezing bed is capable of exceeding the maximum bed loading rates of open drying beds.

DEVELOPMENT OF DESIGN MODELS

The previous study demonstrated that all three sludges drained within minutes after freeze-thaw. Therefore, the design depth will not be limited by the drainage rate, at least to a depth of 2.0 m. Instead, the design depth will be limited by the duration and intensity of the freezing and thawing seasons. The purpose of this section is to develop a mathematical relationship that can be used to design a freezing bed based on local climatic conditions.

Basic energy balance relationship

A relationship between time, temperature and depth of freezing and thawing can be developed from the first law of thermodynamics, which states that energy can neither be created nor destroyed but only changed from one form to another. Thus, the net flow of energy into and out of a system at equilibrium must equal the change in stored energy in the system. In this case the system is a layer of liquid sludge bounded at the top by air and at the bottom by previously frozen layers of sludge.

For any thermodynamic system, a general energy balance may be written as follows (Lunardini 1981):

$$Q + W + M + R = E \quad (1)$$

where Q = net heat energy transferred across system boundaries

W = net mechanical work across system boundaries

M = net flow of energy carried into the system with the mass flow

R = energy developed within the system by electrical, chemical and nuclear means

E = change in stored energy.

For a sludge freezing bed, W , M and R will all be zero. Therefore eq 1 can be reduced to

$$Q = E. \quad (2)$$

Heat energy (Q) can be transferred by three methods: conduction (Q_k), radiation (Q_r) and convection (Q_c). Conduction is a process by which heat flows from a region of higher temperature to a region of lower temperature within a medium or between different mediums in physical contact. During heat flow by conduction, energy is transferred by direct molecular interaction. Radiation is a process by which heat flows from a high-temperature body to a low-temperature body when the bodies are separated. Heat transfer by radiation becomes increasingly important as the temperature of the object increases. Convection is a process of energy transport between a solid surface and a liquid or gas. This mechanism does not depend solely on temperature difference but upon the mixing motion of the fluid as well. Subdividing net heat transfer according to these mechanisms yields

$$Q_k + Q_r + Q_c = E. \quad (3)$$

By taking the derivative of each term with respect to time t , eq 3 becomes

$$\frac{dQ_k}{dt} + \frac{dQ_c}{dt} + \frac{dQ_r}{dt} = \frac{dE}{dt} \quad (4)$$

or in a simpler terminology

$$q_k + q_c + q_r = e. \quad (5)$$

The rate of heat transfer by conduction (q_k) is

$$q_k = \frac{AK}{y} \Delta T \quad (6)$$

where A = surface area perpendicular to the direction of heat flow

K = thermal conductivity of the material

y = thickness of material

ΔT = temperature difference across the material.

The rate of heat transfer by convection (q_c) is

$$q_c = \bar{h}_c A (\Delta T) \quad (7)$$

where A = surface area

\bar{h}_c = average convective heat transfer coefficient

ΔT = temperature difference between surface and fluid.

Solar radiation will be a main source of heat transfer into a freezing bed. Terrestrial radiation (radiation from the earth to the bed) should not be a factor because the bed surface cannot "see" any part of the earth. Diffuse radiation from the atmosphere will not be significant because it amounts to only 10% of the total direct radiation reaching a horizontal surface on a bright sunny day (Kreith 1973).

A black sludge could emit radiation to the atmosphere on cold, clear nights if there is no snow on the roof. This would cause the sludge to freeze more quickly. However, this source of radiation was not included in this analysis because the frequency of this should be minimal.

From Kreith (1973) the rate of heat transfer by solar radiation (q_r) is

$$q_r = \alpha \tau \bar{I} A \quad (8)$$

where α = solar absorptance of the sludge

τ = transmittance of the roof

\bar{I} = average insolation

A = surface area.

The net rate of heat transfer by convection, conduction and radiation must equal the rate of change in stored energy (e). When the sludge is in a liquid state, e can be calculated from

$$e = c \rho_l A \epsilon \frac{dT}{dt} \quad (9)$$

where c = specific heat

ρ_l = density of liquid material

ϵ = depth of liquid material.

During the phase transfer from a liquid to a solid state,

$$e = \rho_f L A \frac{dy}{dt} \quad (10)$$

where

ρ_f = density of solidified material

L = latent heat of fusion.

By substituting the above equations into energy balance relationships, mathematical models for predicting the design depth of a freezing bed are developed below.

Development of freezing model

The process of freezing each layer will take place in two phases. During phase I, liquid sludge will be cooled to the freezing point. During phase II, liquid sludge at the freezing point will be converted to a frozen solid by loss of the latent heat of fusion. Further cooling of the layer below the freezing point should not be significant because the operational plan calls for immediate application of the next layer as soon as the previous layer has frozen (see the *Final Concept* section).

Phase I model

During phase I the liquid sludge cools from its initial temperature (T_0) to its freezing temperature (T_f). For simplicity, it is assumed that the average ambient air temperature during this cooling period (\bar{T}_{ac}) will be at or below the freezing point. The underlying ice temperature (T_i) should be at or near the freezing point if the bed is operated according to plan. The assumed temperature profile in the bed during this phase should be approximately as shown in Figure 15.

This system will lose heat by convection at both the sludge/air and sludge/ice boundaries. There are no heat losses by conduction although it is the intermediate process by which internal heat is transferred to the boundaries. Under these conditions,

$$q_{ca} + q_{ci} = e \quad (11)$$

where q_{ca} = rate of convective heat transfer across the sludge/air interface

q_{ci} = rate of convective heat transfer across the sludge/ice interface.

From eq 7, q_{ca} can be expressed as

$$q_{ca} = \bar{h}_c A (T_s - \bar{T}_{ac}) \quad (12)$$

where T_s = sludge temperature at time t .

The rate of heat transfer across the sludge/ice interface (q_{ci}) can be estimated based on recent work by Lunardini et al. (1986). Studies of a water layer over ice indicate that the rate of heat transfer is constant at water temperatures greater than or equal to 3.4°C . At temperatures below 3.4°C the rate of heat transfer decreases linearly to zero as the temperature approaches zero. Since sludges are mostly water they should behave similarly. Therefore,

$$q_{ci} = 488.5A \quad \text{for } T_s \geq 3.4^\circ\text{C} \quad (13)$$

and

$$q_{ci} = 135.7A(T_s - T_f) \quad \text{for } T_f \leq T_s \leq 3.4^\circ\text{C}. \quad (14)$$

Substituting eq 9, 12 and 13 into eq 11 gives an energy balance relationship for $T_s \geq 3.4^\circ\text{C}$

$$\bar{h}_c A (T_s - \bar{T}_{ac}) + 488.5A = -c\rho_f A \epsilon \frac{dT_s}{dt}. \quad (15)$$

The rate of change in stored energy in this case is negative because the sludge temperature is decreasing. By cancelling the area term (A) and separating variables, eq 15 becomes

$$dt = \frac{-c\rho_f \epsilon dT_s}{\bar{h}_c(T_s - \bar{T}_{ac}) + 488.5}. \quad (16)$$

At $t = 0$, $T_s = T_0$ (the initial sludge temperature); and at $t = t_{cl}$ (time to cool sludge to 3.4°C), $T_s = 3.4^\circ\text{C}$. By integrating between these limits eq 16 becomes

$$t_{cl} = \frac{c\rho_f \epsilon}{\bar{h}_c} \ln \frac{\bar{h}_c(T_0 - \bar{T}_{ac}) + 488.5}{\bar{h}_c(3.4 - \bar{T}_{ac}) + 488.5}. \quad (17)$$

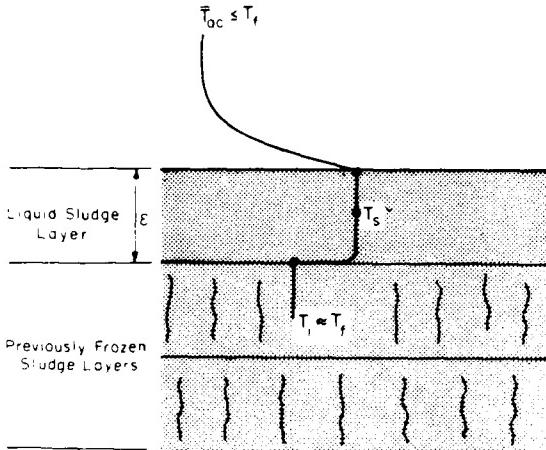


Figure 15. Assumed temperature profile during phase I.

When sludge temperature reaches 3.4°C or in a situation where sludge is applied at a temperature equal to or below 3.4°C , the second rate equation (eq 14) applies. An energy balance relationship for $T_f \leq T_s \leq 3.4^{\circ}\text{C}$ yields

$$\bar{h}_c A(T_s - \bar{T}_{ac}) + 135.7 A(T_s - T_f) = -c \rho_f A \epsilon \frac{dT_s}{dt}. \quad (18)$$

Again, by canceling the area term (A) and separating variables, eq 18 becomes

$$dt = \frac{-c \rho_f \epsilon dT_s}{(\bar{h}_c + 135.7)T_s - \bar{h}_c \bar{T}_{ac} - 135.7 T_f}. \quad (19)$$

At $t = 0$, $T_f < T_s < 3.4^{\circ}\text{C}$ and at $t = t_{c2}$ (time to cool sludge from T_s to the freezing point), $T_s = T_f$. Integrating between these limits results in the following expression for t_{c2} :

$$t_{c2} = \frac{c \rho_f \epsilon}{\bar{h}_c + 135.7} \ln \frac{(\bar{h}_c + 135.7)T_s - \bar{h}_c \bar{T}_{ac} - 135.7 T_f}{\bar{h}_c(T_f - \bar{T}_{ac})}. \quad (20)$$

Note that as \bar{T}_{ac} becomes closer to T_f , t_{c2} approaches infinity. This happens because the rate of heat loss is a function of the temperature difference between the sludge and the ambient air. As this temperature difference becomes smaller, the rate of heat transfer decreases but it never equals zero. This situation could occur in the springtime when average air temperatures are closer to the freezing point. Operationally, this means that applications to a freezing bed should cease well before the end of the freezing season.

When the initial temperature (T_0) is greater than 3.4°C , the total time needed to cool the sludge to the freezing point is the sum of t_{c1} and t_{c2} .

When the initial sludge temperature (T_0) is below 3.4°C , then the total cooling time is equal to t_{c2} .

Phase II model

During phase II, liquid sludge at the freezing temperature (T_f) will be converted to frozen sludge at the same temperature by removing the latent heat of fusion. Sludge will begin to freeze at the top and gradually proceed downward until the layer is completely frozen. Latent heat will be conveyed by conduction to the ice/air interface where it will dissipate into the atmosphere by convection. The expected temperature profile within a freezing bed during phase II is shown in Figure 16.

From eq 6, the rate of heat transfer by conduction (q_k) across a frozen layer of thickness y can be expressed as

$$q_k = \frac{A K_{fs}}{y} (T_f - \bar{T}_{ia}) \quad (21)$$

where K_{fs} is the thermal conductivity of the frozen sludge and \bar{T}_{ia} is the average temperature of the sludge at the air/ice interface.

From eq 7, the rate of heat transfer by convection (q_c) to the atmosphere can be expressed as

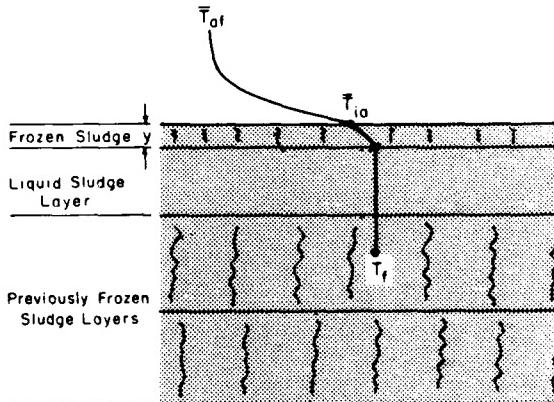


Figure 16. Assumed temperature profile during phase II.

$$q_c = \bar{h}_c A (\bar{T}_{ia} - \bar{T}_{af}) \quad (22)$$

where \bar{T}_{af} is the average ambient air temperature during freezing.

Neither of the above expressions is very useful in practical applications because \bar{T}_{ia} is difficult to determine. However, by solving eq 21 and 22 for the temperature differences $(\bar{T}_{ia} - \bar{T}_{af})$ and $(T_f - \bar{T}_{ia})$ and adding, \bar{T}_{ia} can be eliminated. The result of this mathematical manipulation is the following:

$$T_f - \bar{T}_{af} = \frac{q_k y}{A K_{fs}} + \frac{q_c}{\bar{h}_c A}. \quad (23)$$

Because all heat transfer is upward to the atmosphere, the rates of heat loss by conduction and convection must be equal. Substituting q_c for q_k in eq 23 and solving for q_c yields

$$q_c = \frac{A(T_f - \bar{T}_{af})}{\frac{y}{K_{fs}} + \frac{1}{\bar{h}_c}} \quad (24)$$

which must also equal e , the change in stored energy. Therefore,

$$\frac{T_f - \bar{T}_{af}}{\frac{y}{K_{fs}} + \frac{1}{\bar{h}_c}} = -\rho_f L \frac{dy}{dt}. \quad (25)$$

Separating variables causes eq 25 to become

$$\frac{T_f - \bar{T}_{af}}{\rho_f L} dt = -\left(\frac{y}{K_{fs}} + \frac{1}{\bar{h}_c}\right) dy. \quad (26)$$

At $t = 0$, $y = \epsilon$; and at $t = t_f$, $y = 0$. Integrating eq 26 between these limits results in

$$t_f = \frac{\rho_f L \epsilon}{T_f - \bar{T}_{af}} \left(\frac{1}{\bar{h}_c} + \frac{\epsilon}{2K_{fs}} \right). \quad (27)$$

Ramsay (1971) selected this solution for a simulation model of natural freezing of sludge in lagoons or drying beds. Also, this solution is the same as that presented by Adams et al. (1960) for the case of ice bridge formation by layer freezing.

Examination of eq 27 indicates that convection is the primary heat loss mechanism. This can be recognized by comparing the relative magnitudes of the convection ($1/\bar{h}_c$) and conduction ($\epsilon/2K_{fs}$) terms. By use of typical K_{fs} , \bar{h}_c and ϵ values of 2.21 W/m \cdot °C, 7.5 W/m \cdot °C and 0.08 m, respectively, the convection value (0.1333) is almost one order of magnitude larger than the conduc-

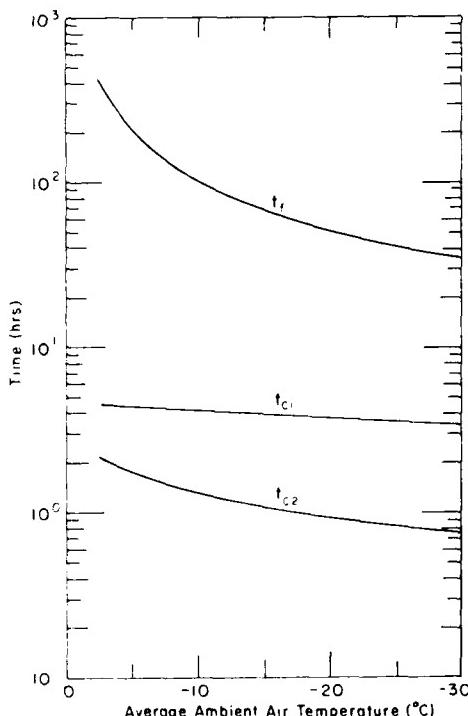


Figure 17. Predicted cooling and freezing curves for an 8-cm sludge layer with an initial temperature of 35°C.

tion value (0.0181). The conduction term does not equal the convection term until the layer thickness is 0.6 m or greater.

If \bar{h}_c is assumed to approach infinity and $T_f = 0^\circ\text{C}$, eq 27 is simplified and the depth of freezing can be determined from

$$\epsilon^2 = \frac{2\bar{T}_{af}K_{fs}t_f}{\varrho_f L}.$$

This solution, developed by J. Stefan (Ingersoll et al. 1954), is often used to predict lake ice thickness. However, this model generally overestimates the depth of freezing because of the assumption that \bar{h}_c is infinite (Environment Canada 1979).

Analysis of models

An analysis was conducted to determine the relative importance of each model (eq 17, 20 and 27) for predicting the total cooling and freezing time ($t_{c1} + t_{c2} + t_f$). This analysis was conducted for the most extreme case when the initial sludge is hot and temperature (T_0) is expected to be high. For most water and wastewater applications this would occur when anaerobically digested sludge was pumped directly from the digester onto the freezing bed. The temperature of this sludge could be as high as 35°C .

Specific heat (c), sludge density (ϱ_f , ϱ_f), latent heat (L), thermal conductivity (K_{fs}) and freezing point (T_f) values used in this analysis are those of water and ice. These values are $1.16 \text{ W}\cdot\text{hr/kg}\cdot{}^\circ\text{C}$, 998 kg/m^3 , 917 kg/m^3 , $93 \text{ W}\cdot\text{hr/kg}$, $2.21 \text{ W/m}\cdot{}^\circ\text{C}$ and 0°C respectively. A later evaluation will show that these values are also valid for sludges (see the *Summary* subsection of the *Evaluation of Sludge Input Parameters* section). The average convective heat transfer coefficient (\bar{h}_c) was assumed to equal $7.5 \text{ W/m}^2\cdot{}^\circ\text{C}$ based on experiments conducted in a prototype freezing bed (see the *Convection Coefficient, \bar{h}_c* section). To simplify this analysis, the average ambient air temperatures during cooling and freezing (\bar{T}_{ac} and \bar{T}_{af}) were assumed to be equal.

A plot of each model (Fig. 17) indicates that t_{c1} and t_{c2} are small compared to the total cooling and freezing time. For example, at $\bar{T}_{ac} = -10^\circ\text{C}$, t_{c1} and t_{c2} are 4.2 and 1.3 hours, respectively, and collectively represent only 5.0% of the total cooling and freezing time (108.8 hours). Therefore, for design purposes, both t_{c1} and t_{c2} could be eliminated from freezing time predictions without serious error. This elimination simplifies the freezing model to only one equation, i.e. eq 27.

Development of thawing model

Thawing will proceed downward from the surface and inward from the walls of the freezing bed. As thawing continues, solids will accumulate on the submerged frozen surface causing an insulating effect. Therefore, the sludge at the bottom of the bed will take longer to thaw than the sludge at the top. The expected temperature profile in the bed during thaw is shown in Figure 18. Essentially, it is a reverse image of the temperature profile during phase II (Fig. 16).

To maximize the thawing rate, most of the supernatant should be removed as quickly as possible. This can be accomplished in the freezing bed by removing the stop-planks as thawing progresses. Also, the sludge should not be allowed to dry because air will be introduced into the open pores. This will reduce the thawing rate because air has a lower conductivity than water.

Since sludge is typically dark, it should absorb solar radiation and heat up quickly during sunny days. This added heat will increase the surface temperature and speed up the thawing process. Therefore, solar radiation was included in the thawing model.

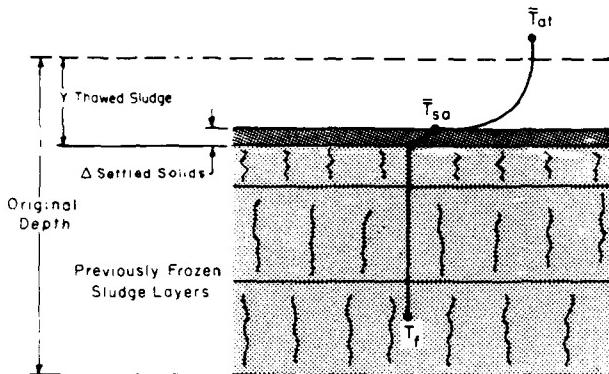


Figure 18. Assumed temperature profile during thaw.

Another source of heat will be from convection, as warm air flows over the frozen surface.

The rate of heat transfer by both mechanisms must equal the rate of energy gain resulting from the phase change from frozen to liquid states. Thus, an energy balance per unit area at the sludge/air interface yields $q_c + q_r = e$, or

$$\bar{h}_c(\bar{T}_{at} - \bar{T}_{sa}) + \alpha\tau\bar{I} = \varrho_f L \frac{dy}{dt} \quad (28)$$

where \bar{T}_{at} is the average ambient air temperature during thaw.

Another energy balance relationship can be obtained across the settled solids layer. The rate of heat transfer by conduction across the settled solids layer must also equal e because both heat transfer processes are acting in series. Thus an energy balance across this layer yields $q_k = e$ or

$$\frac{K_{ss}}{\Delta}(\bar{T}_{sa} - T_f) = \varrho_f L \frac{dy}{dt} \quad (29)$$

where Δ is the depth of settled solids and K_{ss} is the thermal conductivity of the settled solids.

Neither eq 28 nor 29 is very useful because \bar{T}_{sa} is difficult to determine. However, as was done in the freezing model, \bar{T}_{sa} can be eliminated by solving eq 28 and 29 for the temperature differences and adding. This procedure results in the following expression in terms of \bar{T}_{at} and T_f only:

$$\bar{T}_{at} - T_f = \left(\frac{1}{\bar{h}_c} + \frac{\Delta}{K_{ss}} \right) \varrho_f L \frac{dy}{dt} - \frac{\alpha\tau\bar{I}}{\bar{h}_c}. \quad (30)$$

Solving eq 30 can be simplified by assuming that the ratio of Δ to y is constant for all depths. Then Δ can be expressed as θy , where θ is the fraction of deposited solids per unit depth of thawed sludge. Substituting this expression into eq 30 and separating variables results in

$$\left(\bar{T}_{at} - T_f + \frac{\alpha\tau\bar{I}}{\bar{h}_c} \right) dt = \left(\frac{1}{\bar{h}_c} + \frac{\theta y}{K_{ss}} \right) \varrho_f L dy. \quad (31)$$

At $t = 0$, $y = 0$ and at $t = t_{th}$ (time to thaw), $y = Y$ (the total depth of thawed sludge). Integrating between these limits and solving for t_{th} results in the following mathematical model for predicting thawing time:

$$t_{th} = \frac{\varrho_f L Y}{\bar{T}_{at} - T_f + \frac{\alpha \tau \bar{I}}{\bar{h}_c}} \left(\frac{1}{\bar{h}_c} + \frac{\theta Y}{2K_{ss}} \right). \quad (32)$$

Other models

Farrell et al. (1970) conducted several freezing experiments at Ely, Minnesota, to determine the freezing rate of aluminum hydroxide sludges. They adopted the following model for predicting freezing time for a layer with a depth of ϵ :

$$t_f = \frac{\varrho_f L \epsilon}{3600(\bar{T}_f - \bar{T}_{af})K_{fs}} \left(\frac{\epsilon}{2} + 1 \right) \quad (33)$$

where $\varrho_f = 0.917 \text{ g/cm}^3$, $L = 80 \text{ cal/g}$, $K_{fs} = 0.0057 \text{ cal/cm}^2 \cdot \text{s}$, ϵ is in centimeters, and T_f , \bar{T}_{af} are in degrees Celsius. This empirical equation is dimensionally inconsistent and must be used with the units given. The data they obtained from bench-scale studies agreed reasonably well with this model, although a safety factor of 2.0 was recommended when this model is used for design.

Reed et al. (1985) and Hernebring and Lagesson (1986) recommend using a modified version of the Stefan equation. In modified form this equation is

$$t_f = \frac{24}{\bar{T}_f - \bar{T}_{af}} \left(\frac{\epsilon}{m} \right)^2 \quad (34)$$

where ϵ is the layer thickness in centimeters and m is a proportionality coefficient dependent on thermal conductivity, density and latent heat of fusion. Based on three experiments in a pilot-scale drying bed, Reed et al. (1985) found the value of m to be $2.04 \text{ cm}/(\text{°C} \cdot \text{day})^{1/2}$.

As pointed out earlier (*Phase II Model* section), a major assumption of the Stefan model is that the convective heat transfer coefficient is infinite. This assumption makes the surface temperature equal to the ambient air temperature. Under high wind conditions and greater ice thicknesses this assumption may be valid. However, for thin layers such as those applied to a freezing bed the surface temperature is closer to the freezing point than the ambient air temperature. This phenomenon was observed by Adams et al. (1960) during layer freezing experiments with seawater. Data obtained during convection coefficient measurements concur with this observation. Therefore, freezing times predicted by the Stefan model will be less than actual and a freezing bed designed with this model could be seriously undersized.

EVALUATION OF SLUDGE INPUT PARAMETERS

Eight physical and thermal properties of sludge must be determined before eq 27 and 32 can be used to predict freezing and thawing times. These include the physical properties of ϱ_f , ϵ and θ , and the thermal properties L , K_{fs} , K_{ss} , α and T_f . The following is an analysis of each of these variables.

Frozen sludge density, ϱ_f

The specific gravities of all three sludges tested during the drainage and drying experiments (see the *Dewaterability Studies* section) were nearly equal to 1.0. This is typical of most sludges because they contain mostly water, and organic solids have a specific gravity almost equal to that of water. Therefore, the difference in density between frozen sludge and ice should be negligible. The density of ice is 917 kg/m^3 , which is the value used for ϱ_f .

Layer thickness, ϵ

As shown in eq 27, the freezing time is directly proportional to ϵ . Therefore, the thinnest layer possible should be applied to minimize freezing time. However, the application of very thin layers is not practical because the layer would probably freeze before it became evenly distributed. This will result in a buildup of frozen sludge near the inlet end, and the full capacity of the bed would not be utilized. Based on experience with sludge applications to a frozen drying bed (see Appendix A), the layer thickness should be greater than 5.0 cm. Reed et al. (1985) concluded that a layer thickness of 8.0 cm would be practicable.

Settled solids fraction, θ

The settled solids fraction, θ , is the ratio of the depth of settled solids to the depth of thawed sludge. The value of θ will depend on solids content and compressibility. A sludge with a high solids content will have a greater θ value than the same sludge with a lower solids content. Also, a compressible sludge will have a lower θ value than a noncompressible sludge.

Values of θ for the sludges used in the previously described drainage tests are shown in Table 6. The average values were 0.34, 0.15 and 0.07 for the anaerobically digested, aerobically digested and water treatment sludges respectively.

Table 6. Depth of settled solids from drainage tests and calibration of settled solids fraction.

Sludge type	Column number	Thawed sludge depth (cm)	Settled solids depth (cm)	Settled solids fraction, θ
Anaerobically digested	2	220	55	0.25
	4	110	38	0.35
	6	60	22	0.37
	8	34	13	0.38
Aerobically digested	2	220	27	0.12
	4	110	14	0.13
	6	60	9	0.15
	8	34	6	0.18
Water treatment	2	242	16	0.07
	4	132	8	0.06
	6	66	5	0.08
	8	33	2	0.06

Thermal conductivities, K_{fs} , K_{ss}

Because of its high water content, sludge should have the same thermal conductivity as ice, which is 2.21 W/m·°C. The actual K_{fs} value could be slightly higher because the solids generally have a higher conductivity than ice.

There was no information in the literature on the thermal conductivity of settled solids (K_{ss}). However, the thermal conductivities of water and mud are 0.55 and 0.87 W/m·°C, respectively (Ingersoll et al. 1954). The water content in mud ranges from 150 to 300% (Lunardini 1981), which is equivalent to a solids content of 40 to 25%. Data from the drainage tests indicate that the solids content of thawed sludge will also be in this range. Based on this information, the value of K_{ss} was assumed to equal that for mud, which is 0.87 W/m·°C.

Latent heat of fusion, L

The L value for a sludge will be directly proportional to its water content (Lunardini 1981). Pure water has a latent heat of 93.0 W·hr/kg. For a sludge containing 95% water by weight, L will be 88 W·hr/kg. In this study the pure water value for L was used because it results in a slightly more conservative design.

Absorptance, α

Absorptance is the ratio of the solar energy absorbed by a body to total amount that falls on it. For an ideal black body the absorptance would be 1.0. Since sludge is nearly black it should have a very high absorptance. As expected, no values of solar absorptivity for sludge were found in the literature. However, a reported value for dry plowed ground, which is similar in color, is 0.9 (Lunardini 1981).

Freezing point, T_f

Although there appears to be no sludge freezing point information in the literature, a considerable amount of work has been done to determine the freezing point of other substances with high water contents, such as foods and soils. Heldman (1974) explains that water in a food product can freeze over a wide range of temperatures. This phenomenon is attributed to an increase in the salt concentration of the solute as ice is formed. Salts depress the freezing point, and additional freezing will not occur until the temperature is lowered. Hsieh et al. (1977) present freezing points for several foods, including asparagus (-0.67°C), cherries (-1.44°C) and plums (-2.28°C). This same phenomenon can occur in soils. For silts and clays the temperature depression can be as much as 5°C (Lunardini 1981).

A depressed freezing point could have a significant effect on the freezing and thawing times predicted by eq 27 and 32. Consequently, it was necessary to measure freezing points experimentally. These experiments were conducted in the CRREL soils laboratory during December 1985 with the same three sludges used in the previous drainage and drying studies. A photo of the device used to measure freezing points is shown in Figure 19. The basic components of this device were a refrigerated circulating bath (Endocal Model RTE, 400), a spe-



Figure 19. Apparatus used to measure the freezing point of sludge.

cially fabricated stainless steel sample container, and a temperature recorder (Kaye Digistrip III). A thermistor, with an accuracy of $\pm 0.1^\circ\text{C}$, was used to measure temperature.

Before each test, the sample container was cooled to -8°C . A 20-mL sample was then poured into the container and allowed to freeze. As freezing progressed, the elapsed time and temperature inside the sample were recorded. A total of nine tests were conducted, three for each type of sludge.

A typical freezing point depression curve is shown in Figure 20. This curve was obtained while freezing a sample of aerobically digested sludge containing 1.4% solids. Examination of Figure 20 indicates that the sample became supercooled down to -2.2°C after an elapsed time of four minutes. At this time, nucleation occurred, after which the temperature quickly rose to the freezing point. For the next six minutes, the temperature remained essentially constant because of the latent heat released during the freezing process. The average temperature at the freezing point was -0.0480°C . After the phase change was complete, the temperature of the sample began to decrease below freezing.

The results of each freezing point measurement, along with the solids content, is shown in Table 7. Analysis of these data indicate that none of the sludges tested exhibited a large depression of freezing point. Based on these results it was concluded that the freezing point of sludge (T_f) is essentially equal to that of water, i.e., 0°C .

Summary

As a result of these evaluations, it seems reasonable to conclude that the physical and thermal properties of water and wastewater sludges are approximately equal to those of water. The differences that exist are negligible and not significant for design purposes. The main reason for the similarity between sludge and water properties is the high water content in most sludges, which controls thermodynamic behavior. The value of each sludge property determined by this study is summarized in Table 8.

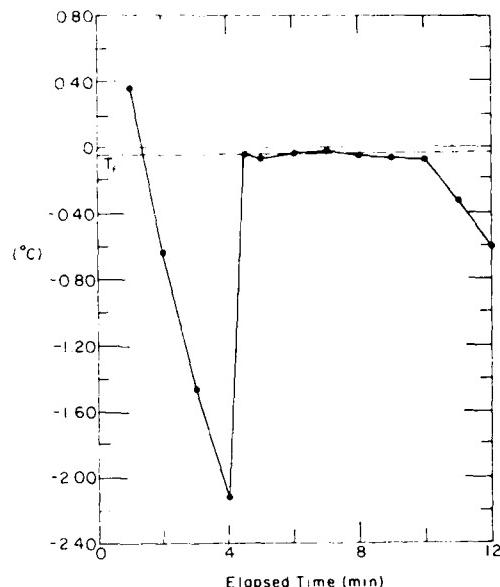


Figure 20. Freezing point depression curve for aerobically digested sludge containing 1.4% solids.

Table 7. Results of freezing point measurements.

Sludge type	Solids content (%)	Freezing point (°C)
Water treatment	0.3	-0.0933
	0.5	-0.0787
	1.1	-0.0730
Anaerobic	3.7	-0.1406
	7.7	-0.1450
	11.2	-0.1030
Aerobic	0.5	-0.0399
	0.9	-0.0380
	1.4	-0.0480

Table 8. Physical and thermal properties of sludge.

Property	Value
ρ_f	917 kg/m ³
L	93.0 W·hr/kg
K_{fs}	2.21 W/m·°C
K_{ss}	0.87 W/m·°C
T_f	0°C
α	0.9

EVALUATION OF CLIMATIC INPUT PARAMETERS

The climatic parameters needed for the freezing and thawing models include the average ambient air temperatures during freezing and thawing (\bar{T}_{af} , \bar{T}_{at}), the average insolation (\bar{I}) and the average convection coefficient (\bar{h}_c). This section will discuss methods to determine these parameters for a proposed site.

Ambient air temperatures, \bar{T}_{af} , \bar{T}_{at}

Air temperature data should be obtained from the meteorological station nearest to the proposed site. In the U.S. there are approximately 350 first-order weather stations that publish monthly average air temperatures. By use of these data, \bar{T}_{af} can be calculated by averaging the monthly average air temperatures that are below freezing. For a conservative design, a warmer-than-normal year should be selected. Likewise, \bar{T}_{at} can be calculated by averaging the monthly air temperatures that are above freezing. In this case, a cooler-than-normal year should be selected for a conservative design. An example of how \bar{T}_{af} and \bar{T}_{at} can be determined from monthly temperature data is shown in the *Use of Models for Design* section.

Insolation, \bar{I}

Insolation is the rate of direct solar radiation on a horizontal surface. Since a freezing bed will also present a horizontal surface to the sun, the use of this parameter is appropriate. Historical solar radiation data can be found in the *Climatic Atlas of the United States* (USGPO 1968) and in Kreith and Kreider (1978). These data are given in Langleys per day, which can be converted into units of W/m^2 as follows:

$$\text{W/m}^2 = \frac{\text{Langley}}{\text{day}} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{11.6 \text{ W}\cdot\text{hr/m}}{\text{Langley}}.$$

The amount of radiation reaching the surface of the bed will depend on the transparency of the roof. A relative measure of transparency is the transmittance (τ), which is the ratio of the radiant energy transmitted to the radiant energy incident on the surface. Transmittance values for various materials can be found in Kreith and Krieder (1978). For example, a roof made of Plexiglas has a transmittance of 0.9.

Convection coefficient, \bar{h}_c

The convection coefficient will vary from day to day depending on the wind conditions. It will also vary areally within a large system such as a sludge freezing bed. These variations are caused by differences in air velocity due to surface geometry. As a result, some sections of the bed will freeze faster than others. To ensure complete freezing before the next layer is applied, the convection coefficient used for design should be based on the slowest freezing portion of the bed.

The magnitude of the convection coefficient will depend on the velocity of air flow over the surface. An approximate value of \bar{h}_c can be obtained from the relationship (Kreith and Krieder 1978)

$$\bar{h}_c = 5.7 + 3.8v \quad (35)$$

where \bar{h}_c is in $\text{W/m}^2 \cdot ^\circ\text{C}$ and v is the wind velocity in m/s. If there is no wind, the air will still move because of air density differences between the warm air near the surface and the colder air above. This sets up a circular flow pattern called free or natural convection. Free convection values of \bar{h}_c range from 6.0 to 30.0 $\text{W/m}^2 \cdot ^\circ\text{C}$ (Kreith 1973). On an open surface in near-

ly still air, Adams et al. (1960) obtained an \bar{h}_c value of $11.6 \text{ W/m}^2 \cdot ^\circ\text{C}$ in layer freezing experiments with seawater.

To obtain a representative value of \bar{h}_c , a series of freezing experiments were conducted in a prototype freezing bed. During the freezing of each layer, the average ambient air temperature (\bar{T}_{af}) and the freezing time (t_f) were recorded. These variables along with the known variables ϵ , ρ_f , L , K_{fs} and T_f were substituted into eq 27 and solved for \bar{h}_c .

Description and operation of prototype freezing bed

An in-ground concrete test cell, previously used for land treatment studies, was converted to a prototype freezing bed. Located at CRREL, the test cell is 9 m square by 1.5 m deep. To convert it to a freezing bed, a transparent Fiberglas roof was built over the test cell. The peak of the roof was cantilevered to provide an opening for ventilation while keeping out precipitation. Both gabled ends were left open except for a latticework of wood strips placed 3 cm apart. The purpose of the latticework was to allow free ambient air movement within the bed while keeping out most of the drifting snow. A door and catwalk provided access to the bed. The inside concrete walls were covered with a petroleum-based foundation coating to prevent leakage. Photos of the prototype freezing bed are shown in Figure 21.

Since previous studies indicated that their physical and thermal characteristics were similar, layers of water rather than sludge were used in these experiments. The point of application was near the center of the bed at an average rate of 66.2 L/min. A splash plate suspended beneath the application point prevented erosion of ice by the water. The average temperature of the water was 5°C , and a typical application took less than 1 hour.

Temperatures within the freezing bed were monitored by 33 copper-constantan thermocouples. Thermocouples 1 through 30 were mounted at 5-cm intervals on a wooden staff. This staff was located on the north side of the bed, approximately 30 cm from the concrete wall. Thermocouples 31, 32 and 33 were suspended above the staff and were used to record ambient air temperature. All thermocouples were attached to a data logger that recorded hourly temperature readings. The system was calibrated with an ice bath to an accuracy of $\pm 0.5^\circ\text{C}$.

The original purpose of the thermocouple string was to automatically apply the next layer of water as soon as the previous layer had frozen and the ambient air temperature was below freezing. However, it soon became apparent that this technique would not work. The thermocouple spacing was too great to detect complete freezing within each layer and the string was located too close to the sidewall. Since freezing began at the sides and progressively moved inward, the thermocouples indicated a frozen state prematurely. Instead of applying each layer automatically, each layer was applied manually after the completeness of freezing was checked by chipping holes in the layer at several locations.

Although the thermocouple string did not operate as an automatic control device, it provided an excellent opportunity to observe the vertical temperature profile within the bed. Figure 22 shows the average vertical temperature profile and standard deviation bands during freezing of the last layer, layer 10. The temperatures shown are hourly averages over the 192-hour freezing period from 3 March 1986 to 11 March 1986.

The shape of this profile closely resembles that of the assumed temperature profile of the phase II model (Fig. 16). Values for \bar{T}_{af} , \bar{T}_{ia} and T_f were -4°C , -1°C and 0°C , respectively. Note that the average surface temperature (\bar{T}_{ia}) of layer 10 is approximately 3°C higher than the ambient air temperature. This difference indicates that convection controlled the rate of heat loss. Otherwise, if conduction alone were controlling, the average surface temperature would equal the average ambient air temperature.



a. Snow-covered roof of bed with lattice work at gabled end.



b. Inside of bed after freezing a water layer.

Figure 21. Prototype freezing bed used to determine the average convection coefficient, \bar{h}_c .

Results

Visual observations revealed that freezing of each layer began from the top surface and around the edges of the bed. As freezing progressed, water was forced towards the middle. Eventually, the surface would rupture near the center of the bed because of the pressure buildup and water would be released. This would happen repeatedly until all the water was frozen. As a result, a mound of ice protruded above the surface after freezing was complete.

From 23 December 1985 to 12 March 1986, 11 layers were applied ranging in thickness from 0.025 m to 0.102 m. A leak developed in the bed during a "January thaw," which caused loss of water during freezing of layers 6, 7 and 8. The suspected location of the leak was along a seam between the poured concrete walls and the footing. Eventually the leak

sealed (probably by freezing) and the lost water was slowly replaced and frozen. To speed up the replacement process, several thin layers were applied until the cavities were filled and a smooth surface was restored. Results of the freezing bed experiments are summarized in Table 9.

Excluding layer 1 because of incomplete freezing, the \bar{h}_c values ranged from 6.0 to 8.3 W/m²·°C. The average \bar{h}_c for the entire freezing period was 7.5 W/m²·°C. According to data supplied by the local meteorological detachment, the average wind speed during this period was 1.0 m/s. From eq 35 the calculated \bar{h}_c value is 9.5 W/m²·°C, which is higher than the experimental value by 2.0 W/m²·°C. One reason for this difference could be the below-ground-level location of the freezing surface. This location could reduce wind velocities especially in the prototype bed where the depth is large in relation to the surface area. This sheltering effect would not be as pronounced in a full-scale bed where the depth-to-surface-area ratio would be smaller.

USE OF MODELS FOR DESIGN

Freezing design depth

Based on the previous analysis of input parameters it is reasonable to assume values of 917 kg/m³, 93 W·hr/kg, 2.21 W/m·°C, 0.08 m and 0°C for ρ_f , L , K_{fs} , ϵ and T_f , respectively. Substituting these values in eq 27 reduces the predicted freezing time, t_f , to

$$t_f = - \frac{6822}{\bar{T}_{af}} \left(\frac{1}{\bar{h}_c} + 0.018 \right). \quad (36)$$

Equation 36 does not predict the freezing design depth directly but only the time needed to freeze one 8-cm layer. The freezing design depth will depend on the number of layers that can be frozen during the freezing period. This can be calculated by dividing the length of the freezing period by the freezing time for each layer. In mathematical terms,

$$D_f = \frac{0.08 P_f}{t_f} \quad (37)$$

where D_f = freezing design depth (m)

P_f = freezing period (hr)

0.08 = assumed depth of each layer (m).

By substituting eq 36 into eq 37,

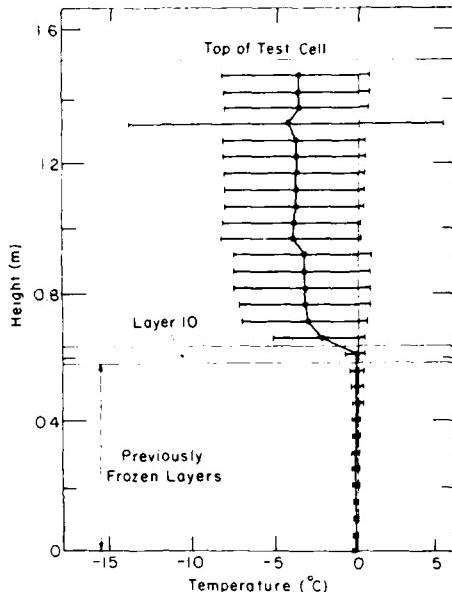


Figure 22. Average temperature profile during freezing of layer 10.

Table 9. Results of prototype freezing bed experiments in Hanover, New Hampshire.

<i>Applied Date</i>	<i>Time</i>	<i>Frozen Date</i>	<i>Time</i>	<i>Layer no.</i>	<i>Freezing time, t_f (hr)</i>	<i>Avg. ambient air temp., T_a (°C)</i>	<i>Layer thickness, ε (m)</i>	<i>Total depth of ice (m)</i>	<i>Calc. conv. coeff., h_c (W/m²·°C)</i>	<i>Remarks</i>
23 Dec 85	0830	26 Dec 85	1500	1	78.5	-5.8	0.076	0.076	18.9	Water was not frozen at deep end of bed before layer 2 was applied.
30 Dec 85	0730	7 Jan 86	0730	2	192.0	-4.7	0.076	0.152	8.2	
7 Jan 86	0900	13 Jan 86	0800	3	143.0	-6.1	0.076	0.228	8.5	
13 Jan 86	0900	15 Jan 86	0730	4	46.5	-13.0	0.051	0.279	7.8	
15 Jan 86	1000	17 Jan 86	0730	5	45.5	-16.5	0.064	0.343	8.1	Air pockets visible below surface of ice layer. Leak suspected in bed.
17 Jan 86	0800	—	—	6	—	—	0.056	0.399	—	Air pockets visible below surface of ice layer. Ice cores confirm presence of 3 cm of water at bottom of ice.
24 Jan 86	0800	—	—	7	—	—	0.058	0.457	—	Air pockets visible below surface of ice layer. Ice cores confirm presence of 3 cm of water at bottom of ice.
29 Jan 86	1300	—	—	8	—	—	0.025	0.483	—	Leak was sealed by natural freezing.
19 Feb 86	1000	3 Mar 86	0700	9	285.0	-5.6	0.102	0.584	6.2	
3 Mar 86	0700	11 Mar 86	0930	10	192.0	-4.0	0.051	0.635	6.0	
12 Mar 86	0830	—	—	11	—	—	0.025	0.152	—	Layer did not freeze because of warm weather.

$$D_f = \frac{-1.17 \times 10^{-5} (\bar{T}_{af} P_f)}{\frac{1}{h_c} + 0.018} . \quad (38)$$

Thawing design depth

By use of the same values for ρ_f , L , T_f and \bar{h}_c as in the freezing model, and by assuming values of 0.9, 0.9 and 0.87 W/m·°C for α , τ and K_{ss} , respectively, the thawing model (eq 32) can be reduced to

$$t_{th} = \frac{85,281 Y}{\bar{T}_{at} + 0.11\bar{I}} \left(\frac{1}{7.5} + \frac{\theta Y}{1.74} \right) . \quad (39)$$

In this case the predicted thawing time (t_{th}) applies to the total depth of frozen sludge and not just an individual layer as in the freezing model. The thawing design depth is the total depth of frozen sludge (Y).

Y can be determined from eq 39 using the quadratic formula. This will produce two values for Y but only the positive value is useful for engineering applications. By use of this approach, the thawing design depth can be predicted from

$$Y = \frac{(12,927.7 + 19.6\theta t_{th} \bar{T}_{at} + 2.2\theta t_{th} \bar{I})^{1/2} - 113.7}{980\theta} . \quad (40)$$

Validation

The freezing and thawing models could not be comprehensively validated because there are no freezing beds currently in operation. However, limited data on layer freezing in sludge lagoons and drying beds were used to conduct a preliminary evaluation of the freezing model.

The Lakewood Filtration Plant in Duluth, Minnesota, has used natural freezing for sludge dewatering for several years (Schleppenbach 1984). Water treatment sludge is pumped from the bottom of the lagoons and sprayed on the top of previously frozen sludge in 15- to 23-cm layers. Based on the reported average freezing rate of 6.8°C·day/cm, the actual number of degree-days required to freeze these layers would range from 102 to 156°C·day. According to eq 27, the predicted number of degree-days [i.e. $t_f(T_f - \bar{T}_{af})/24$] range from 89 to 151°C·day, which is within 3 to 12% of the actual.

Other freezing tests were conducted at the Salem, New Hampshire, Wastewater Treatment Plant during the winter of 1985–86 (see Appendix A). According to results from these tests, layers 4 and 12 cm thick required 14.4 and 69°C·day, respectively, to freeze. The predicted degree-day requirement from eq 27 was 20 and 68°C·day, respectively. Again there was good agreement between the actual and predicted degree-day values. Based on these data, the freezing model appears to be valid.

Example

The use of eq 38 and 40 for design of a sludge freezing bed is demonstrated in the following example. Two sites were selected for evaluation: Hanover, New Hampshire, and Fairbanks, Alaska. These sites were selected because they have different natural freezing and thawing energies. Hanover, New Hampshire, is typical of the temperate zone while Fairbanks, Alaska, is typical of the subarctic zone. Monthly average air temperatures and insolation data for both sites are shown in Table 10.

Table 10. Monthly average air temperatures and insolation at Hanover, New Hampshire, and Fairbanks, Alaska.

Month	Hanover, New Hampshire*		Fairbanks, Alaska†	
	Temperature (°C)	Insolation (W/m ²)	Temperature (°C)	Insolation (W/m ²)
January	-9.2	70	-23.9	8
February	-7.6	107	-19.7	34
March	-0.2	140	-12.4	103
April	6.0	202	-1.1	182
May	13.4	210	8.7	223
June	17.3	232	14.9	244
July	20.6	249	16.1	210
August	19.2	199	13.1	153
September	13.9	151	7.0	87
October	7.8	98	-3.4	40
November	2.1	66	-15.9	13
December	-4.8	59	-22.8	3

* From Bates (1984).

† From NOAA (1984).

From these data P_f , t_{th} , \bar{T}_{af} , \bar{T}_{at} and \bar{I} were calculated for each site as follows.

For Hanover,

$$P_f = \text{Dec, Jan, Feb, Mar} = 121 \text{ days} \approx 2904 \text{ hours}$$

$$t_{th} = \text{Apr, May, Jun, Jul, Aug, Sep, Oct, Nov} = 244 \text{ days} = 5856 \text{ hours}$$

$$\bar{T}_{af} = \frac{-4.8 - 9.2 - 7.6 - 0.2}{4} = -5.4^\circ\text{C}$$

$$\bar{T}_{at} = \frac{6.0 + 13.4 + 17.3 + 20.6 + 19.2 + 13.9 + 7.8 + 2.1}{8} = 12.5^\circ\text{C}$$

$$\bar{I} = \frac{202 + 210 + 232 + 249 + 199 + 151 + 98 + 66}{8} = 176 \text{ W/m}^2.$$

For Fairbanks,

$$P_f = \text{Oct, Nov, Dec, Jan, Feb, Mar, Apr} = 212 \text{ days} = 5088 \text{ hours}$$

$$t_{th} = \text{May, Jun, Jul, Aug, Sep} = 153 \text{ days} = 3672 \text{ hours}$$

$$\bar{T}_{af} = \frac{-3.4 - 15.9 - 22.8 - 23.9 - 19.7 - 12.4 - 1.1}{7} = -14.2^\circ\text{C}$$

$$\bar{T}_{at} = \frac{8.7 + 14.9 + 16.1 + 13.1 + 7.0}{5} = 12.0^\circ\text{C}$$

$$\bar{I} = \frac{223 + 244 + 210 + 153 + 187}{5} = 183 \text{ W/m}^2.$$

Assuming a conservative value for \bar{h}_c (7.5 W/m²•°C), one can calculate the freezing design depths (D_f) from eq 38:

$$D_f = \frac{-1.17 \times 10^{-5}(-5.4)(2904)}{\frac{1}{7.5} + 0.018}$$

$$D_f = 1.2 \text{ m for Hanover.}$$

For Fairbanks,

$$D_f = \frac{-1.17 \times 10^{-5}(-14.2)(5088)}{\frac{1}{7.5} + 0.018}$$

$$D_f = 5.6 \text{ m for Fairbanks.}$$

The thawing design depth (Y) will depend on the type of sludge applied. As shown in the *Thawed Sludge Fraction θ* section, each type of sludge had a different θ factor. For this example an anaerobically digested sludge was chosen, which has an θ value of approximately 0.34. From eq 40,

$$Y = \frac{[12,927.7 + 19.6(0.34)(5856)(12.5) + 2.2(0.34)(5856)(176)]^{1/2} - 113.7}{980(0.34)}$$

$$Y = 3.0 \text{ m for Hanover}$$

$$Y = \frac{[12,927.7 + 19.6(0.34)(3672)(12.0) + 2.2(0.34)(3672)(183)]^{1/2} - 113.7}{980(0.34)}$$

$$Y = 2.4 \text{ m for Fairbanks.}$$

From these calculations it is apparent that the freezing design depth is the limiting criterion for Hanover. Conversely, the thawing design depth is limiting for Fairbanks. The final depths used in design should be 1.2 m for Hanover and 2.4 m for Fairbanks.

For a 3785-m³/day plant, a total suspended solids concentration of 200 mg/L in the raw sewage, and a 6% solids content in the sludge from the digester, the size of each freezing bed can be calculated as follows:

$$\begin{aligned} \text{Influent solids} &= 200 \text{ mg/L} \times 3785 \text{ m}^3/\text{day} \times 10^3 \text{ L/m}^3 \times 10^{-6} \text{ kg/mg} \times 365 \text{ days/yr} \\ &= 276,305 \text{ kg/yr.} \end{aligned}$$

$$\text{Solids to digester} = 0.6 \times 276,305 \text{ kg/yr} = 165,783 \text{ kg/yr.}$$

$$\text{Solids to freezing bed} = 0.5 \times 165,783 \text{ kg/yr} = 82,892 \text{ kg/yr.}$$

$$\text{Sludge volume} = \frac{82,892 \text{ kg/yr}}{0.06} \times 1.0 \text{ L/kg} \times 10^{-3} \text{ m}^3/\text{L} = 1382 \text{ m}^3/\text{yr.}$$

$$\text{Area} = \frac{1382 \text{ m}^3/\text{yr}}{1.2 \text{ m yr}} = 1152 \text{ m}^2 \text{ for Hanover.}$$

$$\text{Area} = \frac{1382 \text{ m}^3/\text{yr}}{2.4 \text{ m yr}} = 576 \text{ m}^2 \text{ for Fairbanks.}$$

Based on these calculations, the area needed for a freezing bed will be considerably less than that needed for an open drying bed. Assuming a typical solids loading rate of 50 kg/m² (WPCF 1983) the area needed to dry 82,892 kg/yr is 1658 m² in both Hanover and Fairbanks. This area is 44% larger than the freezing bed area in the Hanover case and 187% larger in the Fairbanks case.

Instead of using the freezing bed as the only method for dewatering, a combination of freezing and drying beds could be used. By using a drying bed in the summer and a freezing bed in the winter, both natural dewatering processes would be optimized. Also, very little storage capacity would be required. Based on a five-month discharge to a drying bed and a seven-month discharge to a freezing bed, the size of the freezing and drying bed combination for Hanover would be 1363 m² (691 m² for drying bed and 672 m² for freezing bed). Likewise, for a three-month discharge to a drying bed and a nine-month discharge to a freezing bed, the combination for Fairbanks would require 846 m² (414 m² for drying bed and 432 m² for freezing bed).

The area requirements for each option and location are summarized in Table 11. The lowest area requirement for both locations is the freezing bed only option. However, a storage facility would be needed to store the sludge over the summer months. A more cost-effective alternative may be to reduce the storage requirement by using the freezing and drying bed option.

Table 11. Area requirements for sludge dewatering by natural freezing and drying beds (m²).

<i>Location</i>	<i>Drying bed only</i>	<i>Freezing bed only</i>	<i>Combination freezing and drying beds</i>
Hanover, New Hampshire	1658	1152	1363
Fairbanks, Alaska	1658	576	846

CONCLUSIONS AND RECOMMENDATIONS

The improved dewaterability of water and wastewater sludges after freeze-thaw has been known for some time. In most cases, application of this technology has been limited to drying beds and lagoons. However, to optimize the natural freeze-thaw process, a specially designed unit operation is necessary. This study proposes a new dewatering unit operation called a freezing bed. Criteria needed to design this unit operation are developed. The main conclusions of this study are:

1. The depth of sludge that can be applied to a freezing bed is not limited by drainability—at least to a depth of 2.0 m. Since all sludges drained easily at 2.0 m, even greater depths may be possible.
2. The solids content in freeze-thaw conditioned water treatment and anaerobically digested sludges is high enough to allow mechanical removal immediately after drainage is com-

plete. There is no need for further drying. However, further dewatering by drying may be necessary for freeze-thaw conditioned aerobically digested sludge.

3. Capillary suction time (CST) is a better indicator than specific resistance for measuring the dewaterability of freeze-thaw conditioned sludges.

4. The physical and thermal characteristics of frozen sludge are, for engineering purposes, equivalent to those of ice.

5. The design of a freezing bed will depend on the duration and intensity of the freezing and thawing seasons at the proposed site. In a temperate zone, the design depth will be controlled by the freezing season, while in subarctic regions, the length and intensity of the thawing season will be controlling.

Further research is needed to demonstrate the sludge freezing bed concept and to validate the design models. The best way to accomplish this would be to conduct pilot-scale experiments. Also, research is needed to determine the actual thermal conductivity (K_{ss}) of thawed sludge.

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APPENDIX A: SLUDGE FREEZING AT THE SALEM, NEW HAMPSHIRE, WASTEWATER TREATMENT PLANT

Background

The Salem, New Hampshire, Wastewater Treatment Plant was a secondary wastewater treatment plant with an average daily design flow of 9235 m³/day. Sludge produced by the plant was anaerobically stabilized in two digesters and then applied to sand drying beds for final dewatering. There were four beds, each 31 m long by 13.7 m wide. After drying, sludge was raked by hand and removed for ultimate disposal. The plant was shut down in August 1986 because of a consistently overloaded trickling filter that caused odors and complaints from nearby residents.

J. Scafidi, Plant Superintendent, became interested in sludge freezing during the winter of 1985-86 when his digesters became full. He had no place to put the sludge and was considering the expense of hiring a septage pumper to transport it to a disposal site. He came across the report by Reed et al. (1985) that discussed the merits of freezing. He contacted Reed, who relayed the message to me that Scafidi was willing to conduct full-scale sludge freezing experiments on the existing sand drying beds. We agreed to assist him since it would provide data for validation of the sludge freezing model.

Preliminary investigations

Before applying sludge to the beds I wanted to inspect the site and take core samples. On 22 January 1986 I traveled to the site and met Scafidi and J. Olofsson, Project Manager of G and Underwood Engineers, Inc. This engineering firm operated the plant under contract from the City of Salem.

All four beds contained sludge that had already frozen. Two core samples were taken from bed 2, which had received a "double load" of sludge on 7 November 1985. Each core was 17.8 cm long, 15.2 cm of which was frozen sludge. The remaining 2.6 cm was clear ice located at the top of the core. One core sample was taken from bed 3, which had received sludge on 10 December 1985. The depth of sludge in this bed was 11.4 cm, 6.4 cm of which was sludge with the remainder being clear ice, again at the top. The remaining beds (1 and 4) were not sampled because they had received sludge applications earlier in the year and were already dewatered.

The core samples were taken into the plant laboratory where drainage tests were conducted in a modified Imhoff settling cone. This test is described in the "Sacramento Course" and provides a relative measure of drainability. According to this test, a well-drained sludge should produce 100 mL of filtrate within 30 hours. A sample of freeze-thaw conditioned sludge produced 100 mL in less than 10 minutes. This was further proof of the value of freeze-thaw conditioning. A photo of the drainage cone is shown in Figure A1.

Layer freezing tests

Three layers were frozen during the winter of 1985-86. The initial temperature of the sludge was 20°C and the average solids content was 5.7% for all three layers. A maximum-minimum thermometer was used to measure air temperatures during the freezing experiments.

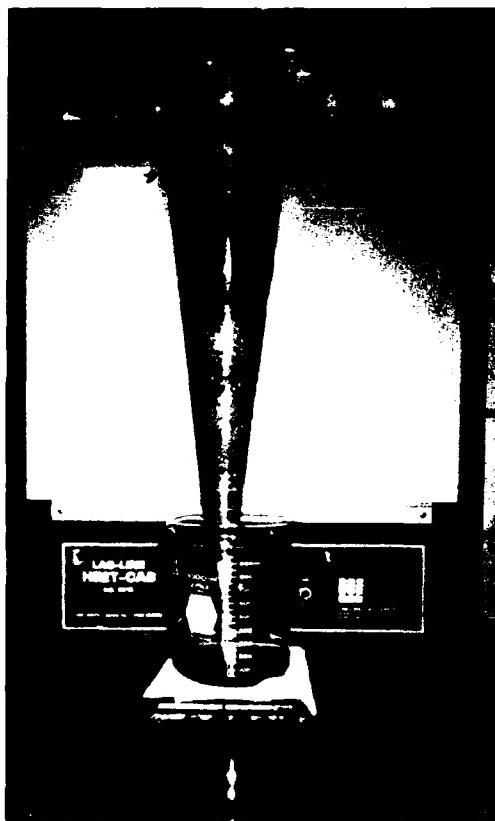


Figure A1. Settling cone used to measure drainability of freeze-thaw conditioned sludge at Salem, New Hampshire.

Layer 1

Application of layer 1 began at 1040 and ended at 1100 on 22 January 1986. The thickness of the layer ranged from 4.4 cm at the far end of the bed to 14 cm at the inlet end. Figure A2 shows photos taken of bed 4 during application of this layer.

Freezing progressed normally until the 26th when 3.3 cm of rain fell on the bed. The rain melted the previously frozen sludge and flooded the drying bed. On the 27th the water drained away through a sinkhole in a corner of the bed, leaving a compacted sludge layer only 4 cm thick. Freezing of this layer was completed by the 30th. According to temperature records, $14.4^{\circ}\text{C}\cdot\text{day}$ were required to freeze this layer.

Layer 2

Layer 2 was applied to bed 3 instead of bed 4 because the sludge in bed 4 was almost at the same level as the invert of the sludge inlet pipe. Applied at 1030 on 31 January, layer 2 was approximately 12 cm thick. On 2, 5, 11 and 17 February, 7.6, 7.6, 2.5 and 5 cm, respectively, of snow and snow mixed with freezing rain fell on the bed. This mixture formed a granular snow layer 5 cm thick on top of the sludge layer.

When I visited the plant on 20 February, layer 2 was frozen at the far end of the bed. At the inlet end, the layer was completely frozen except for approximately 1.0 cm near the bottom of the layer. Based on plant temperature records, $69^{\circ}\text{C}\cdot\text{day}$ were needed to freeze this layer.

Layer 3

To observe the flow characteristics of anaerobically digested sludge, layer 3 was applied to bed 4 on 20 February. It took 33 minutes for the sludge to traverse the length of the bed. The heavier sludge accumulated near the inlet while the lighter sludge and supernatant moved



a. Sludge flowing into bed 4.



b. Sludge spreading over previously frozen layer.

Figure A2. Application of layer 1 in bed 4 of the Salem, New Hampshire, Wastewater Treatment Plant.

ahead. Initially, the depth of sludge at the inlet, middle and end of the bed was 7.6, 5.0 and 2.5 cm, respectively; 21 hours later, measurements in the same approximate locations indicated depths of 5.7, 4.4 and 2.5 cm. From these observations it appears that the minimum thickness for even distribution was approximately 5.0 cm.

Thawed sludge characteristics

Observations of beds 3 and 4 on 4 April 1986 indicated that all the frozen sludge had thawed and drained. The surface was cracked and dry. Based on three measurements, the average depth of sludge in bed 3 was 8.0 cm and 6.0 cm in bed 4. The average solids contents were 38 and 37%, respectively. In comparison, the solids content of sludge from bed 2, which had not received sludge applications over the winter, was about the same at 39%. Superintendent Scafidi was well satisfied with these results and he felt that a considerable cost savings was realized as a result of this operation.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Martel, C. James.

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